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ABSTRACT

This technical specialty course is one of thirty-five courses designed for use by two-year postsecondary institutions in five nuclear technician curriculum areas: (1) radiation protection technician, (2) nuclear instrumentation and control technician, (3) nuclear materials processing technician, (4) nuclear quality-assurance/quality-control technician, and (5) nuclear reactor (plant) operator trainee. This course, Power Plant Systems, contains nine modules: Power Plant Fundamentals, Power Plant Thermal Cycles, Turbines and Generators, Heat Exchangers and Condensers, Pumps, Valves and Piping, Electrical Transmission and Distribution Systems, Power Plant Fundamentals (Fossil Fuel), and Fossil Power Plant Auxiliary Equipment. Each module follows a typical format including the following sections: introduction, module prerequisites, objectives, subject matter, exercises, materials, procedures, data tables, reference materials, and tests. (A master index and suggested program planning guides are also available--see CE 026 856 and CE 026 639-643.) (LRA)

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Nuclear Technology Series
COURSE 10
POWER PLANT SYSTEMS

TECHNICAL EDUCATION RESEARCH CENTER - SW

4201 LAKE SHORE DRIVE - SUITE III

WACO, TEXAS 76710

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P R E F A C E

ABOUT NUCLEAR TECHNOLOGY MODULES

The modules - developed by TERC-SW for use in two-year postsecondary technical institutions to prepare technicians for employment - are useful in industry for updating employees in company-sponsored training, and as laboratory texts in engineering schools. The principles, techniques and skills taught in the modules, based on tasks that nuclear technicians perform, were obtained from a nationwide advisory committee of employers of nuclear technicians. Each module was written by a working technical expert and tested with students.

A module contains the following elements:

Introduction, which identifies the topic and often includes a rationale for studying the material.

Module Prerequisites, which identify the material a student should be familiar with before studying the module.

Objectives, which clearly identify what the student is expected to know for satisfactory module completion. The objectives, stated in terms of action-oriented behaviors, include such action words as operate, measure, calculate, identify and define, rather than words with many interpretations, such as know, understand, learn and appreciate.

Subject Matter, which presents the background theory and techniques supportive to the objectives of the module. Subject matter is written with the technical student in mind.

Exercises, which provide practical problems to which the student can apply this new knowledge.

Materials, which identify the equipment required to complete the laboratory procedure.

Procedures, which is the experiment section, or "hands-on" portion of the module (including step-by-step instruction) designed to reinforce student learning.

Data Tables, which are included in most modules for the first year (or basic) courses to help the student learn how to collect and organize data.

Reference Materials, which are included as suggestions for supplementary reading/viewing for the student.

Test, which measures the student's achievement of the presented objectives.

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The Nuclear Technology Series will consist of five curricula when completed:

- Nuclear Reactor (Plant) Operator Trainee.
- Radiation Protection Technician.
- Nuclear Materials Processing Technician.
- Nuclear Quality-Assurance/Quality-Control Technician.
- Nuclear Instrumentation and Control Technician.

The completed Nuclear Reactor (Plant) Operator Trainee curriculum consists of the following sixteen technical specialty courses made up of 114 instructional modules:

Radiation Physics.	Reactor Auxiliary Systems.
Radiation Protection I.	Power Plant Systems.
Principles of Process Instrumentation.	Radiation Detection and Measurement.
Heat Transfer and Fluid Flow.	Reactor Physics.
Introduction to Nuclear Systems.	Power Plant Chemistry.
Instrumentation and Control of Reactors and Plant Systems.	Introduction to Quality Assurance/Quality Control.
Reactor Operations.	Metallurgy and Metals Properties.
Reactor Safety.	Mechanical Component Characteristics and Specifications.

Availability: Instructional modules are available individually or by courses from:

Technical Education Research Center - Southwest
4201 Lake Shore Dr., Suite 111

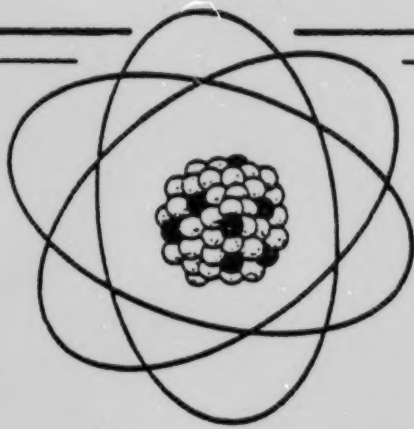
Waco, Texas 76710

Telephone (817) 772-3736

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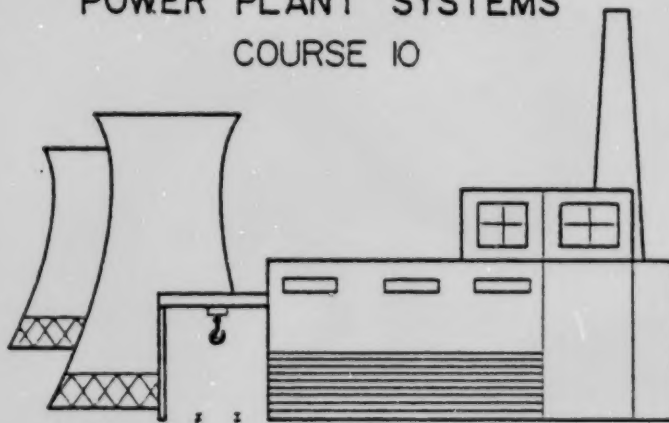
Module 10-1	Power Plant Fundamentals
Module 10-2	Power Plant Thermal Cycles
Module 10-3	Turbines and Generators
Module 10-4	Heat Exchangers and Condensers
Module 10-5	Pumps
Module 10-6	Valves and Piping
Module 10-7	Electrical Transmission and Distribution Systems
Module 10-8	Power Plant Fundamentals (Fossil Fuel)
Module 10-9	Fossil Power Plant Auxiliary Equipment



NUCLEAR TECHNOLOGY

MODULE 10-1 POWER PLANT FUNDAMENTALS

POWER PLANT SYSTEMS
COURSE 10



TEC - SW

TECHNICAL EDUCATION RESEARCH CENTER — SOUTHWEST
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COURSE MODULES

COURSE 10 POWER PLANT SYSTEMS

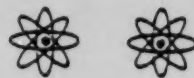


- MODULE 10-1 Power Plant Fundamentals
- MODULE 10-2 Power Plant Thermal Cycles
- MODULE 10-3 Turbines and Generators
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Most electricity is produced in what is referred to as a "steam-electric cycle;" water (in liquid form) is heated to produce steam, as in a tea kettle. This steam rushes past the fan blades of a turbine connected by a driveshaft to an electricity generator.

A generator is just the opposite of an electrical motor (electricity causes rotation of a motor's shaft; rotation of a generator's shaft produces electricity); therefore, as the steam rotates the fan blades, the turbine shaft rotates and drives the generator shaft.

The source of energy for heating the water may be nuclear fission, or the burning of oil, gas or coal (or lignite). Except for the method of heating water, most electrical power generating plants are basically the same. (Note: There are plants in which the generators are driven by internal combustion engines, especially diesel-fired engines; however, such plants are comparatively inefficient and economically impractical.)

This module deals with the fundamental of producing electricity with steam. Subsequent modules in this course cover such essential topics as thermal cycles and specific equipment used in both nuclear and fossil-fuel fired power plants.



MODULE PREREQUISITES

For a finer understanding of power plant fundamentals, student should have basic comprehension of fluid properties (Module 4-1), fluid statics (Module 4-2), fluid dynamics (Module 4-3), heat transfer by conduction (Module 4-4), heat transfer by convection (Module 4-5), heat transfer by radiation (Module 4-6) and change of phase by boiling (Module 4-7), also basic nuclear reactor components (Module 5-1), pressurized water reactors (Module 5-2), boiling water reactors (Module 5-3) and water properties sensing (Module 13-5). If possible, student should have visited a nuclear- or fossil-fueled, steam-driven electrical power generating plant.



OBJECTIVES

Upon completion of this module, the student should be able to:

1. Write a brief summation of the development, harnessing, cause and effect of steam power.
2. Discuss the phenomenon of boiling water, what happens when it boils and the significant parts of the boiling cycle.
3. Describe pressurized water reactor (PWR) and boiling water reactor (BWR) systems; list major differences between the two; draw a flow diagram of each.
4. Describe a basic fossil-fuel fired steam system; com-

pare it with a nuclear-fired system, listing basic differences; draw a flow diagram of each.

5. List basic interactions between main components of a fossil-fuel fired steam system.

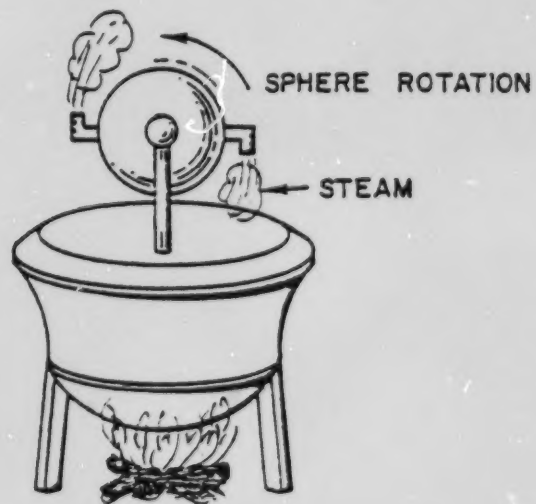


THE EVOLUTION OF STEAM

From the moment man was able to successfully light a fire, he was knowingly creating two other by-products: smoke (or combustion gases) and heat energy. No doubt, the combustion gases were a nuisance to the entire neighborhood, but the energy could be put to good use. A warm drink, cooked food, heat to combat the cold of winter and firelight to keep enemies at bay, all were real possibilities. As time progressed, man learned to heat metals, which - when cooled or quenched in liquids - improved and hastened production of necessities and incidentals.

It was not until the first century A.D. that the energy content of steam was understood or demonstrated (Figure 10-1-1). And it was not until the seventeenth century that

Figure 10-1-1.
Hero's toy engine.



economic needs of a pending industrial society provided useful applications for steam power. Soon thereafter steam devices were built and tested to pull wagons on tracks (steam trams), turn paddle wheels (steam driven boats) and drive mechanical equipment, such as cotton gins.

By 1800, with the Industrial Revolution in full swing, engineers became aware of gross inefficiencies, especially in heat losses, of steam engines. By the late 1800's, many patents had been granted for more efficient uses of fuel energy to convert water to steam. Most important was the use of boiler water tubes (Figure 10-1-2), in which heat energy is transferred from fuel to a boiler by means of several water tubes.

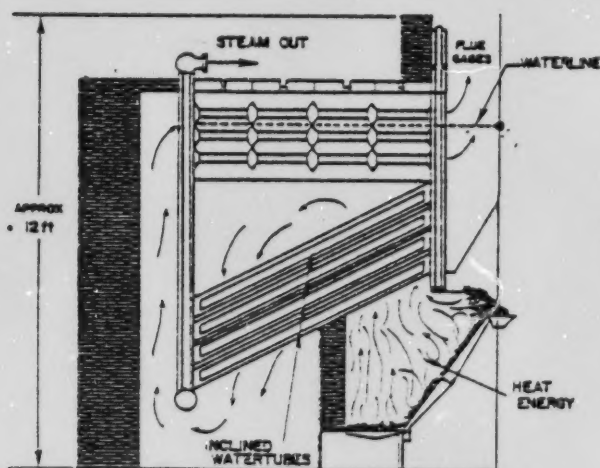


Figure 10-1-2.
Early inclined
water-tube boiler.

In part, this improvement in steam boilers came about as a result of application of steam to electrical power generation. Steam, expanding through a system of pipes, blowing against fan blades (buckets) of a turbine, caused the turbine to rotate, and caused an electrical generator to rotate

by means of a driveshaft that coupled the turbine to the generator (Figure 10-1-3). Utility companies were formed to supply electricity for industrial and residential use on an economical basis. And steam became the major drive medium of electrical utilities around the world.

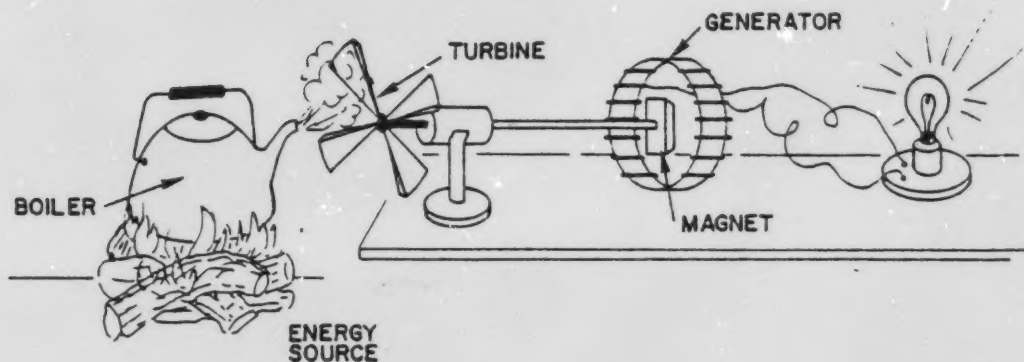


Figure 10-1-3. Simplified, steam-driven power generation system.

STEAM

Steam, which is water in the gaseous or vaporized state, is colorless, odorless and invisible - what can be seen coming out of the spout of a kettle of boiling water is actually droplets of water being carried along by the steam.

The temperature at which water (or any liquid) becomes steam is its "boiling point," or saturation temperature. This temperature is dependent upon pressure (Figure 10-1-4).

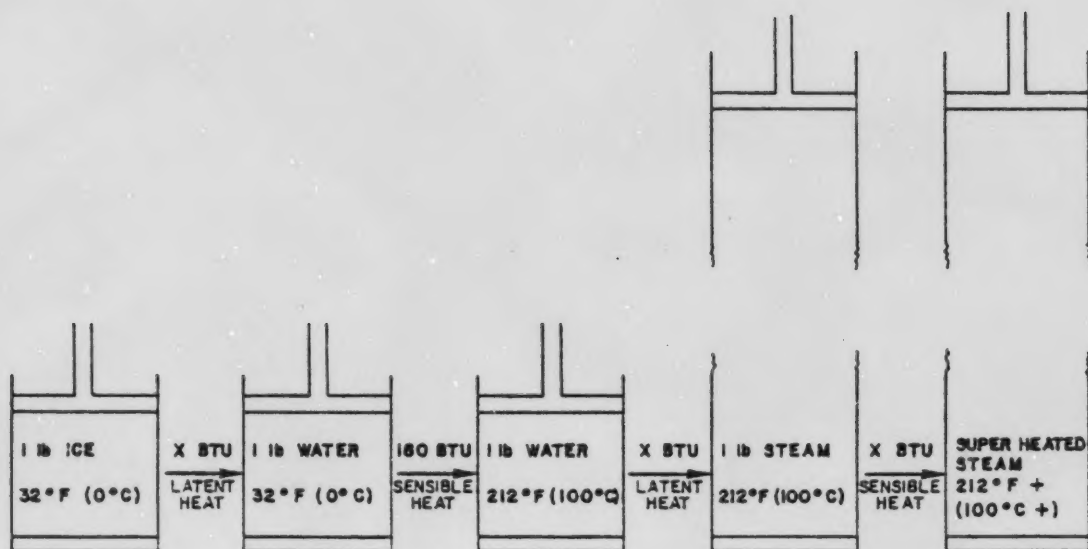


Figure 10-1-4. Total-heat designations through two phase changes (ice → water; water → steam).

At one atmosphere (atmospheric pressure at sea level or zero altitude), the boiling point of water is 212°F (100°C), but under 2000 psia the boiling point of water increases to 635.82°F (325°C). Thus, temperature is a significant term insofar as power plant operation is concerned, but it must not be confused with the term "heat."

HEAT

A useful term in any study of thermal (heat) systems is the British thermal unit (Btu). A Btu is defined as the amount of heat required to raise one pound of water one degree Fahrenheit (1°F) in one atmosphere of pressure. (Conversely, when a pound of water drops one degree Fahrenheit, it loses one Btu.)

EXAMPLE

50 Btu raises 1 lb of water from 70°F to 120°F
(50°).

50 Btu raises 50 lb of water from 70°F to 71°F
(1°).

100 Btu raises 1 lb of water from 70°F to 170°F
(100°).

100 Btu raises 50 lb of water from 70°F to 72°F
(2°).

For simplicity, a Btu is about the amount of heat (thermal energy) derived from burning one kitchen-type wooden match.

For water in the liquid state, the amount of heat added can be calculated as follows:

$$Q = mc_p \Delta t$$

Equation 10-1-1
(Equation = Eq.)

where

Q = heat added, Btu.

m = mass, lb.

c_p = specific heat, Btu/lb °F
= 1 for practical purposes here.

Δt = temperature increase, °F.

EXAMPLE

Given: $m = 5 \text{ lb.}$

$$c_p = 1 \text{ Btu/lb } ^\circ\text{F.}$$

$$\Delta t = 212 - 85 = 127^\circ\text{F.}$$

Find: How much heat must be added to 5 pounds of water at 85°F to reach 212°F ; i.e., Q in Btu.

Solution: $Q = mc_p \Delta t$

$$= (5 \text{ lb}) (1 \text{ Btu/lb } ^\circ\text{F}) (127^\circ\text{F})$$

$$= 635^\circ\text{F.}$$

Heat that causes a change in temperature is known as "sensible heat." Some heat, referred to as "latent heat," shows up as a change in phase (e.g., from liquid to gas) - "latent" means "hidden," which simply implies that it is not seen as a change in temperature.

Latent Heat

The latent heat of fusion (melting) is the heat required to melt ice or change it from a solid into a liquid. At one atmosphere, the latent heat required to melt one pound of ice is 144.0 Btu/lb.

The latent heat of vaporization (changing a liquid into a gas) is the heat required to effect vaporization of a liquid already at its boiling point. At one atmosphere, this value for water 970.4 Btu/lb.

Total Heat

The total heat added is the sum of the sensible heat and the latent heat (if a change of phase is involved). In

the case of heating ice, already at 32°F (Figure 10-1-4), temperature of the mass remains at 32°F until the ice becomes water, even though 144.0 Btu's of latent heat have been added. Once the ice is melted, however, each added Btu increases water temperature through the range from 32°F to 212°F. But, when the temperature reaches 212°F, 970.4 Btu's of latent heat must be added to effect the change of phase from water to steam, even though no temperature increase occurs. As soon as the change of phase occurs, however, the steam temperature begins to climb. NOTE: Steam, at any temperature above 212°F, is referred to as "superheated steam."

EXAMPLE

Given: 100,000 lb of water at 80°F; assume one atmosphere, and that one Btu raises temperature of steam 2°F.

Find: Added heat to change water into 600°F superheated steam.

Solution:

Sensible heat added to liquid

$$\begin{aligned} &= (100,000 \text{ lb}) (212 - 80^\circ\text{F}) \\ &= 1.32 \times 10^7 \text{ Btu.} \end{aligned}$$

Latent heat added

$$\begin{aligned} &= (100,000 \text{ lb}) 788 \text{ Btu/lb} \\ &= 788 \times 10^7 \text{ Btu.} \end{aligned}$$

Sensible heat added to steam

$$\begin{aligned} &= (100,000 \text{ lb}) (600 - 212^\circ\text{F}) \\ &= 1.94 \times 10^7 \text{ Btu.} \end{aligned}$$

Total heat added

$$(1.32 \times 10^7) + (788 \times 10^7) + (1.94 \times 10^7) \\ = 1.114 \times 10^8 \text{ Btu.}$$

(Note: The properties of steam have been theoretically calculated and experimentally verified and are published in the United States as the "Steam Tables." These tables are covered more fully in Module 10-2, "Power Plant Thermal Cycles.")

CLOSED BOILING SYSTEMS

To more fully explain boiling, a closed water boiling system (Figure 10-1-5) may be analyzed. This system consists of a top steam drum (vessel) and a steel tube leading from the bottom of the vessel down through an energy source and back up to the top steam drum.

The circuit, filled with water up to a level in the top drum, leaves space for the generated steam to flow out to drive the steam turbine.

When the system is cold, no circulation takes place - the water assumes a constant level in both legs of the tube. But, as soon as heat is applied to the riser leg, water starts to rise up through the hot "riser" and down the cold "downcomer." As more heat is applied, steam bubbles form in the riser tube, lowering the density of the water and causing it to rise faster into the steam drum. At the same time, the more dense, colder water flows down the downcomer

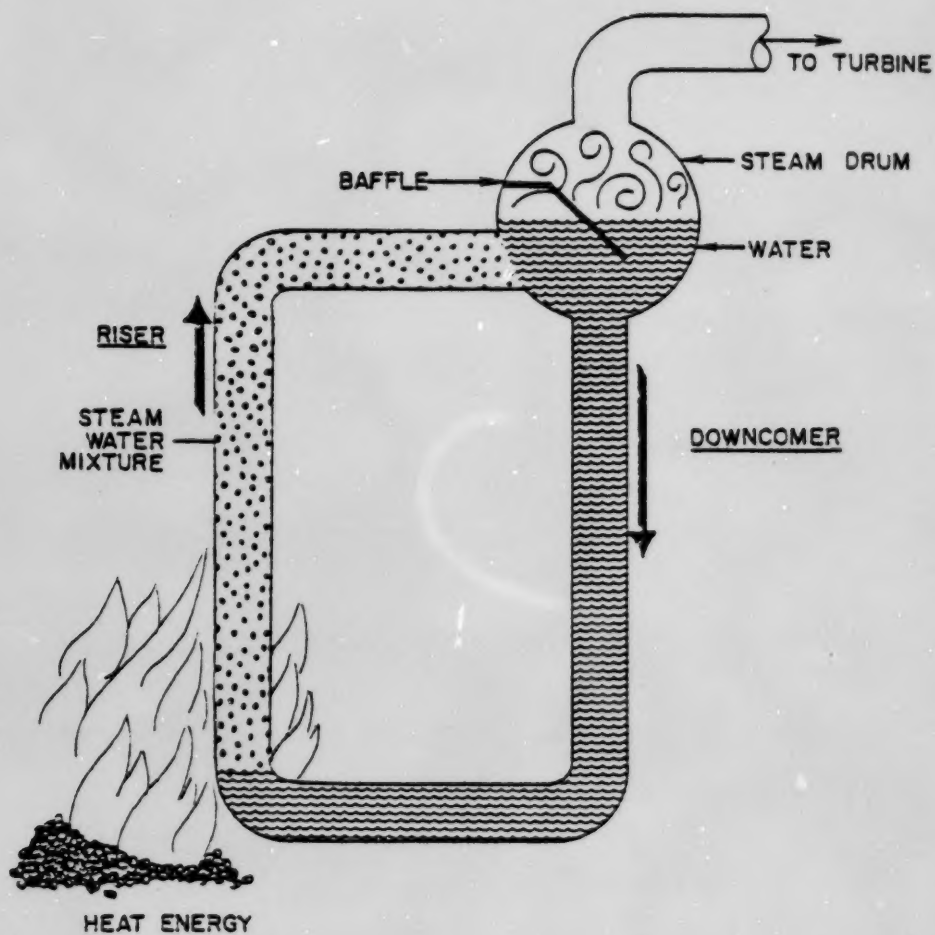


Figure 10-1-5. Closed boiling system.

tube, causing natural circulation. This principle forms the basis on which conventional fossil-fueled steam generation works.

Because of turbulence in the steam drum, caused by the release of the steam, droplets of water are carried by the steam up into the space above the liquid level. These droplets must be removed from the steam going to the turbines -

they cause excessive wear on the turbine blades, deposit salts on the piping and reduce overall efficiency of the system. Internal baffles, steam dryers, and moisture separators, installed in modern boiler drums, keep moisture carryover to a minimum.

To increase steam generation rate, the velocity of water passing through the tubes must be increased, allowing an increase in heat transfer. This velocity increase is achieved by using a high-pressure pump to force water through the tubes. Such an arrangement is referred to as "forced circulation."

NUCLEAR STEAM PLANTS

Since the early research reactors of the 1950's, many types of steam generating power reactors have been designed, built and tested. The most common types used in nuclear power plants are discussed in Course 5, "Introduction to Nuclear Systems." Thus, only a brief review of each type is presented in this module.

PRESSUREIZED WATER REACTOR (PWR)

Heat is transferred to the cooling water in this system by a closed, high-pressure water system (Figure 10-1-6). The cooling water transfers heat through the steam generator to liquid at a reduced pressure, causing the secondary water to boil (i.e., become steam).

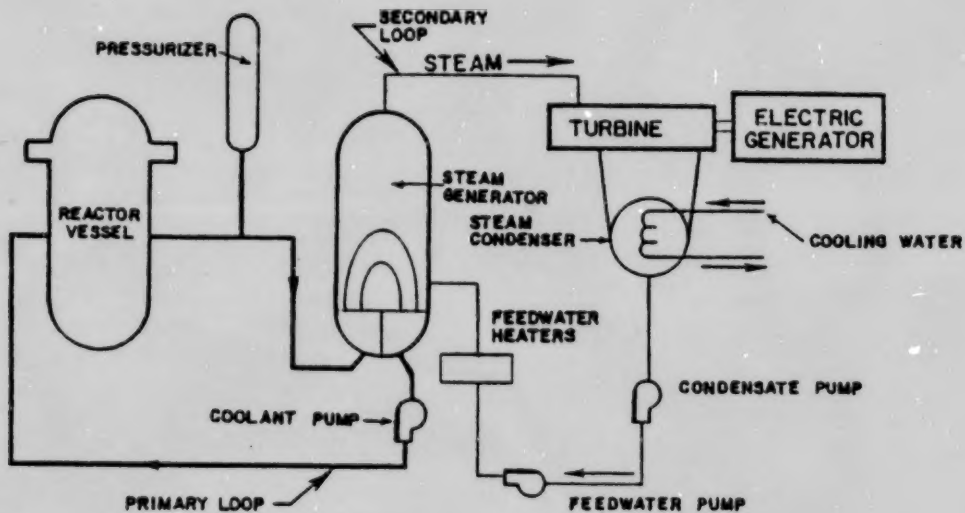


Figure 10-1-6. Primary and secondary pressure system.

Secondary steam flows to the turbines, which convert the internal energy of this steam to mechanical (shaft) work.

The most common arrangement of turbines is one high-pressure and several low-pressure turbines mounted on a common rotating shaft, which in turn is connected to the shaft of an electric generator. Once steam passes through the turbine cycle, giving up most of its energy, its remaining heat is removed in a steam condenser.

BOILING WATER REACTOR (BWR)

In a typical boiling water reactor system, hot water returning from feedwater heaters (Figure 10-1-7) enters the bottom of the reactor vessel and circulates around the fuel core and thermal shield. The steam flows directly

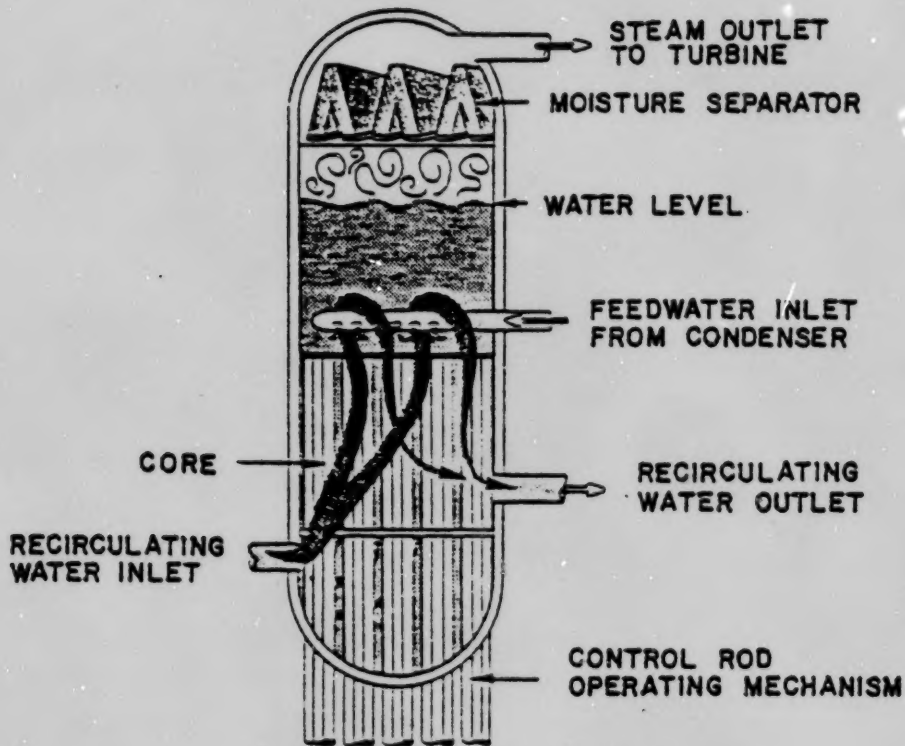


Figure 10-1-7. Cross section of boiling water reactor.

from the boiler to the turbines and then follows a loop cycle, similar to that of a PWR, back to the reactor.

In Circuit 1 (the primary loop), reaction heat is removed from the reactor by pumping a liquid metal (sodium or sodium potassium) through the reactor core. The heat extracted is given up to Circuit 2 (intermediate or secondary loop) through a primary heat exchanger. Circuit 2 also utilizes sodium or sodium potassium liquid to extract heat that is given up to Circuit 3 (working fluid loop) through a steam generator/heat exchanger to the water circuit. Steam then flows through equipment similar to that used in a fossil-fuel plant.

The sodium or liquid metal in Circuit 1 becomes highly radioactive when flowing through the reactor core, which necessitates the use of a secondary loop between Circuit 1 and Circuit 3. Liquid metals have low melting points and high boiling points and, therefore, remain liquid over a wide range of temperatures. They also have excellent heat transfer and fluid-flow properties with high thermal conductivities.

FOSSIL-FUEL STEAM PLANTS

Steam plants obtain their best operating efficiency when steam pressure and temperature reach their highest allowables, and condensing water is simultaneously at its lowest achievable temperature.

Since 1900, power plant designers have steadily increased the throttle steam pressure (Figure 10-1-8). (Note: "Throttle steam pressure" is the pressure of the steam as it enters the turbine.) This increase is a result of the development of super alloys, the high costs of which must be offset by gains in efficiency.

Fossil fuels, in relation to power plant energy, are allocated into four distinct main categories:

- Coal.
- Lignite.
- Oil.
- Gas.

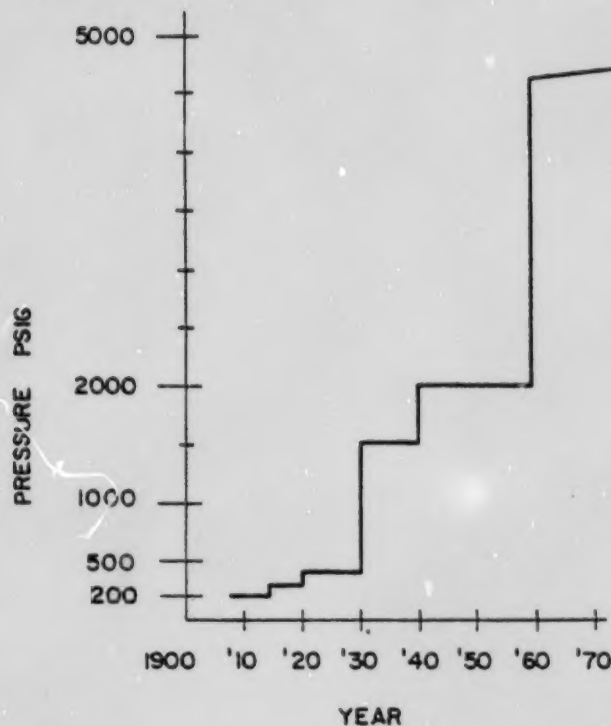


Figure 10-1-8.
Increase in throttle
steam pressure
since 1900.

Power plant location must be such that the cost of transporting fuel to the plant balances with the cost of transmitting electrical power to consumers.

Many millions of years ago, trees, plants and vegetables fell into the surrounding water and decayed, causing "peat bogs." Successive geological upheavals buried these peat bogs under layers of sand and silt, from where the coal is mined today. Coal is considered a primary fuel for burning in steam boilers in any of its mined formations.

Coal has many subcategories, but is comprised throughout of three components:

- Coal itself (organic matter).

- Mineral content (prehistoric plant fibers).

- Moisture (water).

An analysis of coal by chemical means shows the following components to be present:

- Carbon.
- Oxygen.
- Hydrogen.
- Nitrogen.
- Sulfur.
- Ash.
- Water (moisture).

When coal burns under controlled test conditions, it gives up a certain amount of heat, its "heating value." For U.S. coals, this figure ranges from 10,000 Btu/lb to 15,000 Btu/lb, depending upon the source mine location. Therefore, even though it is highly desirable to have a boiler that can burn a wide range of coals, none performs equally as well with every type.

Overall operating costs consist mostly of fuel costs, which - for a single year - could be equal to the initial cost of the entire generating plant.

Those impurities in coal that are not inherent can be removed by economic cleaning methods; however, the undesirable ash-forming sulfur elements are considered inherent and do not leave the coal until it is burned.

Since 1920, coal has been pulverized into small particles before being introduced into a combustion furnace. In the furnace it is thoroughly mixed with combustion air. This procedure eliminates the old chain-conveyor coal-fed stoker and its many maintenance problems.

Lignite (brown coal) is a subcategory of coal that formed when the prehistorical peat bogs of coal vented off gases, allowing the coal to turn to lignite. The largest deposits of lignite in America are found in North Dakota and

and Texas, where mechanical strip-mining methods have been perfected.

The percentage of strip-mined lignite has risen from 3 percent in 1925 to 35 percent in 1968. The heating value for lignite is approximately 6000 Btu/lb and, although the heating value of lignite is much lower than most coals, it also has a much lower sulfur content.

Since conservation of land is of national concern, utility companies throughout the United States restore strip-mined land to its original form (trees, livestock and crops), thereby making the strip mining of lignite an acceptable source of fossil fuel.

Lignite, in a manner similar to coal, is pulverized before it is introduced into a combustion furnace. Boiler designers have come up with a boiler design called a "cyclone" furnace, which is capable of successfully burning a large variety of coals and lignites.

Oil used for firing steam power plants is that portion left after distillation of crude oil to produce gasoline, hydrogen and carbon. Consequently, the amount available as fuel oil depends upon the national demand for these products rather than the type of crude oil used. This oil, like coal, is a mixture of organic compounds, including:

- Carbon.
- Nitrogen.
- Oxygen.
- Sulfur.
- Hydrogen.

Crude oil, regardless of its source, contains these elements within reasonable limits. The heating value for oil is approximately 18,000 to 19,500 Btu/lb, which is considerably higher than either coal or lignite.

Transportation of crude oil for fuel usage is an important economic factor in steam power plant location decisions. Water transportation is the cheapest, approximately nine times cheaper than pipeline transportation, and thirty times cheaper than rail transportation. Another important economic factor considered in site location is fuel oil storage, with associated fire protection.

Boilers that use fuel oil require oil-burning equipment of special design. It must handle large volumes of oil per hour, and atomize the fuel oil to obtain good oil-to-air mixtures. Atomizing - breaking up the oil into a fog - can be achieved by using moisture-free air or steam in the burner nozzle. In addition, the oil must have electrical- or steam-heated supply lines to provide constant viscosity to the burners.

Natural gas generally is found wherever crude oil is found. It has lighter hydrocarbon compounds of methane, ethane, propane and butane. "Bottled" gases - propane and butane - are stored under pressure. When this pressure is released, the liquid boils and produces gaseous fuels.

Natural gas may include two undesirable components: 1) sand, which can be removed at the wellhead, and 2) hydrogen sulfide, which may be removed before the gas is distributed.

The heating value of gas - 700 to 1000 Btu/cu ft - and its ease of transportation (through pipelines) and storage, either above or below ground, make it preferable to oil for fueling power plants.

COAL AND LIGNITE - SUMMARY

The advantages and disadvantages of coal and lignite are as follows:

- No upper limit on size of steam boilers.

- If pulverized, the fuel can be used from a wide range of mining sources.

- Coal and lignite can be used economically over a wide range of boiler capacities.

- Special fuel-preparation equipment - moisture removal and pulverizing - is required.

- Heated air is required for moisture removal in combustion cycle.

- Ash removal equipment, including particulate from the flue gas, is required.

When special furnace-design firing is used:

- Fly-ash particulate and flue-collection equipment can be reduced.

- Furnace size can be reduced.

- Fuel-preparation equipment can be reduced.

NATURAL GAS - SUMMARY

- Least number of design restrictions of all fossil fuels.

- Easy to burn, and burns cleanly.

- Fuel-storage and ash-disposal equipment are eliminated.

- Soot-blowing equipment, ash buildup and erosion are reduced or eliminated.

- Potential hazard of gas accumulation requires special safety detection and alarm systems.

FUEL OIL - SUMMARY

Minimum number of design restrictions.

Ash-disposal equipment is eliminated.

Full storage and pumping facilities are required.

Fuels with high sulfur contents cause deposit problems, and acid attack can occur in air heaters.



EXERCISES

1. Find saturation temperatures corresponding to the following pressures: 14.7 psia, 100 psia, 500 psia, 1000 psia, 1500 psia, 2000 psia and 2500 psia; plot saturation-temperatures versus saturation-pressures.
2. Plot temperature versus heat-added-to-water; give total heat added for the following conditions, all at atmospheric pressure:

Initial temperature = 32°F (ice); final temperature = 200°F; mass = 2 lb.

Initial temperature = 40°F; final temperature = 540°F; mass = 10⁶ lb.

Initial temperature = 150°F; final temperature = 212°F (vapor); mass = 20 lb.

Initial temperature = 212°F (liquid); final temperature = 212°F (vapor); mass = 100 lb.

Initial temperature = 80°C; final temperature = 120°C; mass = 10⁵ gram.



MATERIALS

None.



PROCEDURES

None.



DATA TABLE

None.



Babcock and Wilcox Co. Steam: Its Generation and Use.

New York: B & W, 1975.

Combustion Engineering, Inc. Combustion. Windsor, CT:

Combustion Engineering, Inc.

El-Wakil, M. M. Nuclear Energy Conversion. New York:

Intext Educational Publishers, 1971.

Skrotzki, B. G. and Vopat, W. A. Power Station Engineering

and Economy. New York: McGraw-Hill, 1960.



1. Describe, in terms used in this module, significant facts regarding development, use, cause and effect of steam power:

2. Listed below are several terms used in steam generation; define each:

Sensible heat.

Latent heat.

Wet steam.

Saturated steam.

Superheated steam.

Riser.

Steam drum.

Natural circulation.

Moisture separators.

Forced circulation.

3. In America, two main types of nuclear power plant reactors have been developed and put into commercial use; list each and give its abbreviated title:

4. Sketch a simple flow diagram of each system; identify major components:

2

5. Describe a fossil-fuel steam-generating system cycle (use a simple flow diagram):

6. List five basic differences between a nuclear-fueled power plant cycle and a fossil-fueled power plant cycle:

7. Define, in terms used in this module, the following major items of steam power plants:

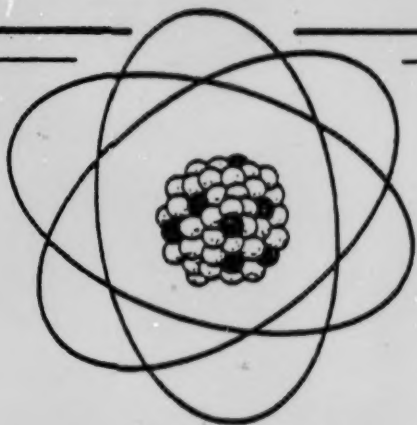
Steam generator - nuclear.

Fossil-fuel steam boiler.

Steam turbine.

Coal fuel.

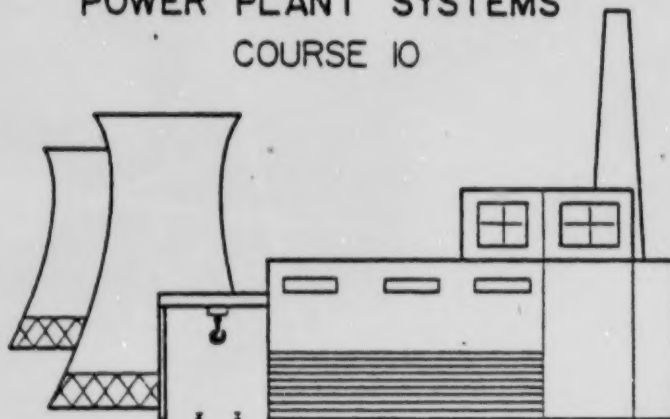
Lignite fuel.



NUCLEAR TECHNOLOGY

MODULE 10-2 POWER PLANT THERMAL CYCLES. -
JAMES R. BOHANNON, JR.

POWER PLANT SYSTEMS
COURSE 10



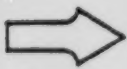
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COURSE MODULES

COURSE 10 POWER PLANT SYSTEMS



MODULE 10-1	Power Plant Fundamentals
MODULE 10-2	Power Plant Thermal Cycles
MODULE 10-3	Turbines and Generators
MODULE 10-4	Heat Exchangers and Condensers
MODULE 10-5	Pumps
MODULE 10-6	Valves and Piping
MODULE 10-7	Electrical Transmission and Distribution Systems
MODULE 10-8	Power Plant Fundamentals (Fossil-Fuel , Energy Efficiency)
MODULE 10-9	Fossil Plant: Auxiliary Discussions

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Technical Education Research Center
Southwest
4201 Lake Shore Drive, Suite 111
Waco, Texas 76710



INTRODUCTION

The term "thermal cycle" refers basically to the process of transferring energy from a heat source (boiler or reactor) to a machine that can generate electricity. The specific cycle used depends on heat source and machine used to accomplish the transfer.

This module discusses the concepts of energy sources, heat, energy transfer, heat engines and work and relates these concepts as a means of converting heat energy to electricity. Also, it introduces basic principles of thermodynamics, and presents those properties of water important to a working fluid. Finally, it presents examples and exercises to demonstrate and apply these concepts and principles.



MODULE PREREQUISITES

The student should have completed courses in basic mathematics and heat transfer as well as Course 3, "Principles of Process Instrumentation," Course 4, "Heat Transfer and Fluid Flow," and Course 5, "Introduction to Nuclear Systems," from this series.



OBJECTIVES

Upon completion of this module, the student should be able to:

1. Define or describe in one or two sentences the following and include units used where applicable:
 - Energy.
 - Work.
 - Flow work.
 - Heat.
 - Thermodynamics.
 - First Law of Thermodynamics (describe).
 - Second Law of Thermodynamics (describe).
 - Properties..
 - Enthalpy.
 - Latent heat of vaporization.
 - Entropy.
 - Specific heat.
 - Specific volume.
 - Saturation temperature.
 - Superheated.
 - Carnot cycle (describe).
 - Rankine cycle (describe).
 - Thermal efficiency.
 - Saturated liquid.
 - Saturated vapor.
 - Carryover.
 - Heat balance.
2. Identify the different types of energy discussed in this module.
3. List the two major thermodynamic cycles and different portions of each (such as reheat-regeneration cycles in

particular); highlight basic cycle differences between nuclear-fueled and fossil-fueled systems.

4. Sketch a typical steam cycle diagram and a T-S plane; reference typical steam conditions.
5. Use values from steam tables included in this module to obtain properties of steam and water at different pressures and temperatures.
6. Explain, with the aid of P-V and T-S diagrams, why lowering condenser coolant temperature and raising steam pressure and temperature increases thermal efficiency of a steam-electric plant.
7. Given a steam table and appropriate equations, perform heat balance and efficiency calculations.



ENERGY AND WORK

To understand heat and energy processes of power plants in general and those of nuclear plants in particular, it is necessary to understand the forms in which energy may be present. (Energy is defined as ability to do work.)

For the moment, work may be defined as a form of mechanical energy (energy used to move an object over some distance). Work done in this manner, with respect to moving an object, is equal to force applied (or used) times distance the object travels:

$$\text{Work} = \text{force} \times \text{distance.} \quad \text{Equation 10-2-1}$$

(Equation = Eq.)

An engine is a means of converting energy to a force that can do work. In a heat engine, a working fluid may undergo a change in its temperature, pressure, or volume, or all three. The working fluid may be a gas or vapor impacting on turbine blades, thus performing work by rotating the turbine shaft. In a steam engine, a chemical or nuclear fuel heats a boiler containing water; the boiling water produces steam that is retained in a closed system to allow its temperature and pressure to rise; the energy of expanding steam translates to mechanical work by driving a turbine.

Heat production from conventional heat sources is controlled by regulating fuel flow into a boiler. Thus, when more power (energy per unit time) is demanded by an engine, more fuel must be fed into its boiler burners by a stoker.

In a nuclear reactor, fuel is a fixed quantity inside a pressure vessel. The heat production process for this system is controlled by natural feedback and, to some extent, by moving control rods: when more power (steam) is demanded by the turbine, the nuclear reactor automatically produces it; rods are withdrawn to adjust fission rate, if necessary, for what is not done automatically.

Involved in these processes are three familiar variables:

Temperature.

Pressure.

Flow of energy-transporting medium.

FORMS OF ENERGY

In describing energy transformation within a power-producing nuclear plant, the important forms include:

"Mechanical" energy (E_m) - Energy associated with mechanical motion and interaction of bodies. This energy is equal to the sum of the potential energy (E_p) and kinetic energy (E_k) of the body [the units are Btu/lb_m (ft - lb_f/lb_m), or (J/kg)]:

$$E_m = E_p + E_k.$$

Eq. 10-2-2

Note: Potential energy, which is possessed by a body due to its relative change in elevation or

position (height), is essentially zero in power plants. Kinetic energy is the energy possessed by a body due to its motion ($1/2 mv^2$).

"Internal" energy - Energy (stored within a body) that may be released to do work. A typical unit would be Btu/lb_m (or J/kg) of fossil or nuclear fuel when burned.

Flow work - If a substance is flowing into or out of a system, it possesses an energy quantity when entering or leaving the system as denoted by Pv , where P is pressure and v is volume. The fluid entering the system exerts a force on the boundary and may do work, for example, by moving a turbine or piston. The symbol in most energy equations utilizes W_f in Btu or $\frac{Pv}{J}$, where J is a conversion factor.

Heat - Energy in transition from one body to another by virtue of a temperature difference existing between them. The symbol for transferred heat is Q , and the units are generally Btu/lb_m (J/kg). Since both work and heat are energy in transition, there exists a relationship between them (foot-pound and Btu):

$$1.0 \text{ Btu} = 778 \text{ ft-lb or } J = 777 \text{ ft-lb/Btu.}$$

"Thermal" energy - Power is energy per unit time and can be expressed in terms of thermal or mechanical energy; i.e., in Btu/hr or megawatts. One megawatt equals 3.43×10^6 Btu/hr. (Mechanical power would be given in ft-lb/s.)

Thermodynamics is the science that deals with heat and mechanical energy, or heat and work. Regardless of the type of work or form of energy considered, the terms heat, work and energy are only meaningful when applied to specific sur-

roundings, systems, processes and cycles. For "expansion" work - in this case steam - the system under consideration is a fluid capable of expansion or contraction under the influence of pressure changes, temperature changes, chemical reactions or all three. The system is said to undergo a cyclic process or cycle if the system changes in form and energy and then returns to its original condition. It is the thermal cycle that is all important in power production. Thus, steam can be considered a thermodynamic system and has become a favored system in power generation and heat transfer.

REVIEW OF PWR AND BWR STEAM SYSTEMS

Because of the extensive discussion to follow with regard to thermal cycles as they relate to electric power generation plants, a review of these plants is in order.

The two most common power reactors in this country are the pressurized water reactor (PWR) and boiling water reactor (BWR).

The PWR (Figure 10-2-1) primary coolant system operating pressure is normally about 2200 psia and 610°F (outlet temperature). In contrast, the primary coolant system pressure in a BWR (Figure 10-2-2) operates at approximately 1000 psia and 600°F outlet temperature. (It will be shown later that these conditions are important in determining cycle type and plant efficiency.

The steam production system (Figure 10-2-3) of a modern fossil-fueled, steam-electric plant is a single reheat,

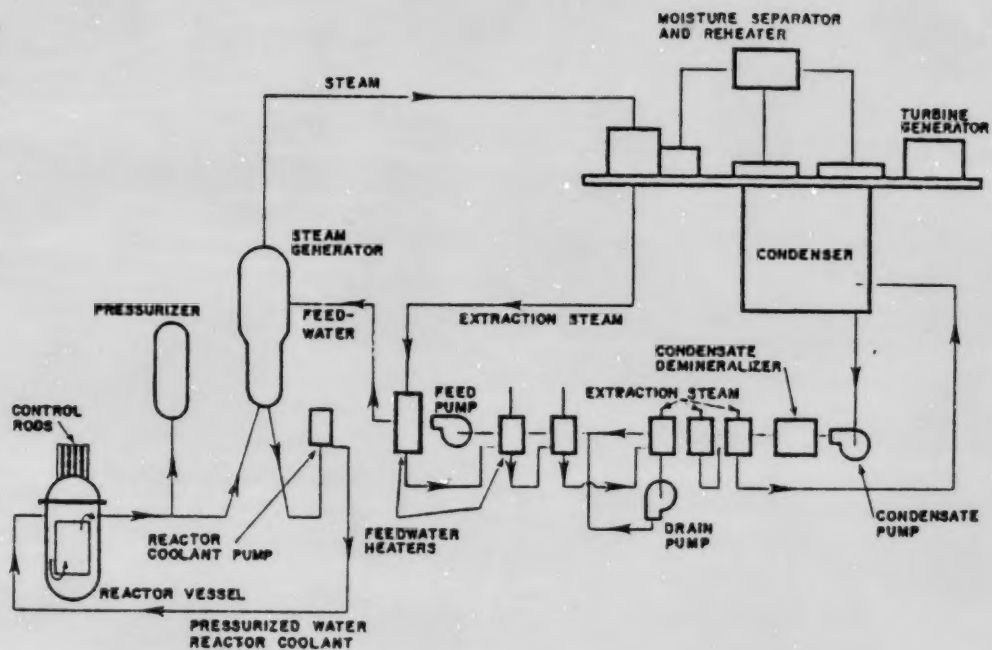


Figure 10-2-1. PWR power plant.

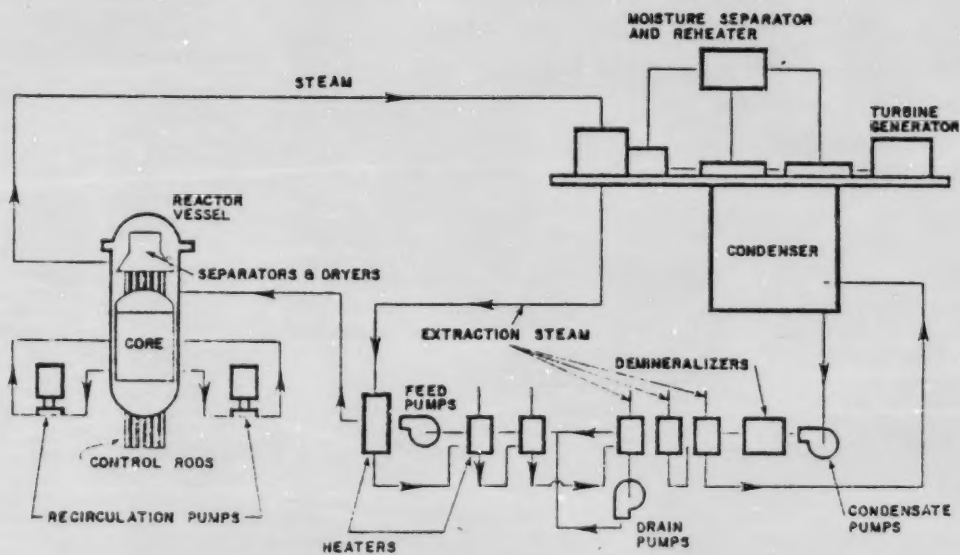


Figure 10-2-2. BWR power plant.

types of heat engines. In a very simple way, this law states that, "You can't get something for nothing." It also establishes the relationship between energies involved when either a transfer or a transformation takes place.

The Second Law of Thermodynamics states:

It is impossible to construct an engine, operating in cycles, that can convert into work all the heat energy supplied to the working substance (like water).

Restated, "You can never break even; you always lose." More energy must be put in than will come out in the form of work.

In preparation for the study of thermal cycles as they apply to steam plants, some review and new and old definitions are in order, and the properties of steam itself must be understood.

Properties are those quantities necessary to describe the state of a substance; that is, how hot or cold it is, how dense it is, at what pressure it exists, and how much volume it occupies.

Enthalpy is a measure of the thermal energy contained in a substance:

$$\text{Enthalpy} = \text{specific heat} \times \text{temp above } 32^{\circ}\text{F}$$

Eq. 10-2-3

where specific heat is defined as ratio of amount of heat required to raise a mass of material 1 degree in temperature to amount of heat required to raise an equal mass of a reference substance, usually water, 1 degree in temperature.

Latent heat of vaporization (h_{fg}) is the amount of heat required to change a pound of water into a pound of steam, with no change in temperature: 970 Btu/lb_m at atmospheric pressure.

Entropy (symbolized S) is a property for internally reversible processes, and it will not be physically described because the definition is extremely complex. It is that portion of the heat cycle that does not produce work, but merely represents an unrecoverable loss.

Note: As the specific volume (volume of a substance per unit mass) of steam decreases with increased pressure and temperature (just the opposite of water), a point is reached at which the specific volume of water and steam are the same (705°F and 3206 psia). This point is called the critical point (Figure 10-2-4).

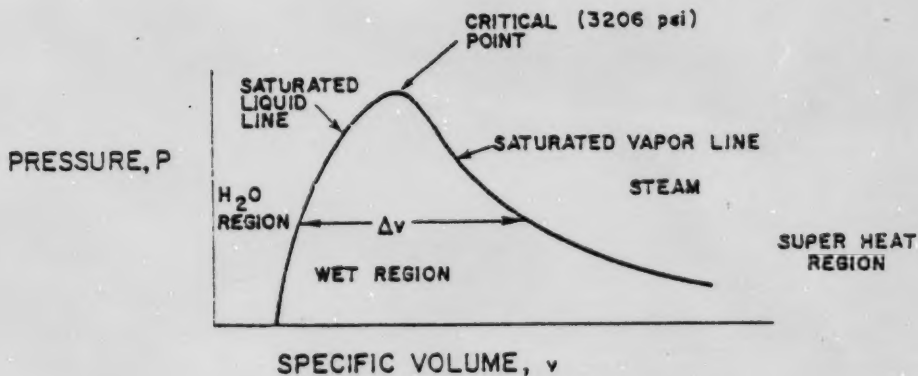


Figure 10-2-4. Phase diagram of water (P-v plane).

The change in specific volume Δv , associated with a change in states (as water becomes steam or the reverse),

can be determined from the graph. The Δv decreases as T (temperature) and P (pressure) increase, the same as that of the steam. Specific volume of steam is v_g (g for gas), that of water is v_f (f for fluid) and Δv is v_{fg} for the mixture.

When heat is added to a liquid being held at a constant pressure, the liquid temperature increases until the saturation temperature or boiling point of that liquid is reached (Figure 10-2-5). A liquid that is below this temperature is

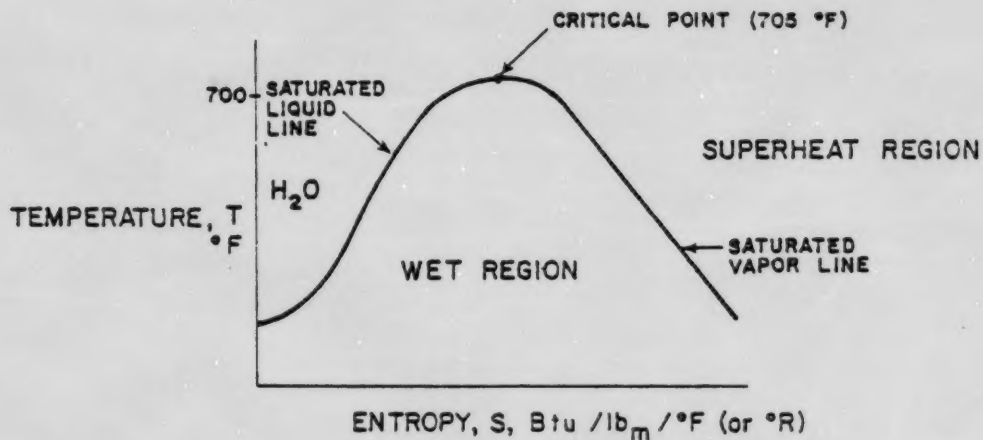


Figure 10-2-5. Phase diagram of water (T-S plane).

said to be a subcooled or compressed liquid. If heat is added until saturation temperature is just reached, it is called a saturated liquid. As more heat is added, the liquid begins to change its phase from a liquid to a vapor; and its condition is denoted by its quality, the percentage of dry steam in the mixture. If sufficient heat is added to completely vaporize the liquid, the vapor is said to be saturated vapor. Further heating causes the temperature to go

up, and it is said to be superheated, i.e., vapor temperature rises above saturation temperature. Steam entering the turbines of nuclear plants is saturated or slightly superheated.

STEAM TABLES (Tables 10-2-1, 10-2-2 and 10-2-3)

Steam tables list numerical values of the thermodynamic properties of water, steam and mixtures. Values in these tables have been obtained from measurements made by scientists, engineers and physicists.

Steam tables are comprised of three sections: two for saturated steam and a third for superheated steam. (Note that the tables attached are not complete for the range of temperature and pressure. Complete tables should be used from the referenced Keenan and Keyes.)

CONSERVATION OF ENERGY: STEADY-FLOW ENERGY EQUATION

The power plant thermal cycle is closed and thus the law of conservation of energy can be applied to yield a steady flow energy equation: the sum of all energies entering a system is equal to the sum of all energies leaving the system.

TABLE 10-2-1
SATURATED STEAM: TEMPERATURE TABLE

Temp F	Press. psia	Volume, ft ³ /lb			Enthalpy, Btu/lb			Entropy, Btu/lb x F			Temp F
		Water v_f	Evap v_{fg}	Steam v_g	Water h_f	Evap h_{fg}	Steam h_g	Water s_f	Evap s_{fg}	Steam s_g	
32	0.08839	0.01602	3305	3305	-0.02	1073.3	1073.3	0.0000	2.1873	2.1873	32
35	0.09991	0.01602	2948	2948	3.00	1073.3	1076.3	0.0061	2.1706	2.1767	35
40	0.12163	0.01602	2446	2446	8.03	1071.0	1079.0	0.0162	2.1432	2.1594	40
45	0.14744	0.01602	2037.7	2037.8	13.04	1068.1	1081.2	0.0262	2.1164	2.1426	45
50	0.17796	0.01602	1704.8	1704.8	18.05	1065.3	1083.4	0.0361	2.0901	2.1262	50
60	0.2561	0.01603	1207.6	1207.6	28.06	1059.7	1087.7	0.0553	2.0391	2.0948	60
70	0.3629	0.01605	868.3	868.4	38.05	1054.0	1092.1	0.0745	1.9900	2.0645	70
80	0.5088	0.01607	633.3	633.3	48.04	1048.4	1096.4	0.0932	1.9426	2.0359	80
90	0.6961	0.01610	468.1	468.1	58.02	1042.7	1100.9	0.1115	1.8970	2.0086	90
100	0.9492	0.01613	350.4	350.4	68.00	1037.1	1105.1	0.1295	1.8530	1.9825	100
110	1.2750	0.01617	265.4	265.4	77.98	1031.4	1109.3	0.1472	1.8103	1.9577	110
120	1.6927	0.01620	203.25	203.25	87.97	1025.6	1113.5	0.1646	1.7693	1.9339	120
130	2.2230	0.01625	157.32	157.32	97.96	1019.8	1117.8	0.1817	1.7295	1.9112	130
140	2.8892	0.01629	122.98	122.98	107.95	1014.0	1122.0	0.1985	1.6910	1.8895	140
150	3.713	0.01634	97.05	97.07	117.95	1008.2	1126.1	0.2150	1.6536	1.8688	150
160	4.741	0.01640	77.27	77.29	127.96	1002.2	1130.2	0.2313	1.6174	1.8487	160
170	5.993	0.01645	62.04	62.06	137.97	996.2	1134.2	0.2473	1.5822	1.8296	170
180	7.511	0.01651	50.21	50.22	148.00	990.2	1138.2	0.2631	1.5480	1.8111	180
190	9.340	0.01657	40.94	40.96	158.04	984.1	1142.1	0.2787	1.5143	1.7934	190
200	11.526	0.01664	33.62	33.64	168.09	977.9	1146.0	0.2940	1.4824	1.7764	200
210	14.123	0.01671	27.80	27.82	178.13	971.6	1149.7	0.3091	1.4509	1.7600	210
212	14.696	0.01672	26.78	26.80	180.17	970.3	1150.5	0.3121	1.4447	1.7568	212
220	17.186	0.01678	23.13	23.15	188.23	963.2	1153.4	0.3241	1.4201	1.7442	220
230	20.779	0.01685	19.364	19.381	196.33	956.7	1157.1	0.3368	1.3962	1.7290	230
240	24.968	0.01693	16.304	16.321	203.45	952.1	1160.6	0.3533	1.3609	1.7142	240
250	29.825	0.01701	13.802	13.819	210.59	948.4	1164.0	0.3677	1.3323	1.7000	250
260	35.427	0.01709	11.745	11.762	228.76	938.6	1167.4	0.3819	1.3043	1.6862	260
270	41.856	0.01718	10.042	10.060	238.95	931.7	1170.6	0.3960	1.2769	1.6729	270
280	49.200	0.01726	8.627	8.644	249.17	924.6	1173.8	0.4098	1.2501	1.6599	280
290	57.550	0.01736	7.443	7.460	259.4	917.4	1176.8	0.4235	1.2238	1.6473	290
300	67.005	0.01743	6.448	6.466	269.7	910.0	1179.7	0.4372	1.1979	1.6351	300
310	77.67	0.01755	5.609	5.626	280.0	902.5	1182.5	0.4506	1.1726	1.6232	310
320	89.64	0.01766	4.896	4.914	290.4	894.8	1185.2	0.4640	1.1477	1.6116	320
340	117.99	0.01787	3.770	3.788	311.3	879.8	1190.1	0.4902	1.0990	1.5892	340
360	153.01	0.01811	2.939	2.957	332.3	862.1	1194.4	0.5161	1.0517	1.5673	360
380	196.73	0.01836	2.317	2.335	353.6	844.3	1198.0	0.5416	1.0057	1.5473	380
400	247.26	0.01864	1.8444	1.8630	375.1	825.9	1201.0	0.5667	0.9607	1.5274	400
420	308.78	0.01894	1.4803	1.4997	396.9	806.2	1203.1	0.5915	0.9165	1.5080	420
440	381.54	0.01926	1.1976	1.2169	419.0	785.4	1204.4	0.6161	0.8729	1.4890	440
460	466.9	0.0196	0.9746	0.9942	441.5	763.2	1204.8	0.6405	0.8299	1.4704	460
480	566.2	0.0200	0.7972	0.8172	464.3	739.6	1204.1	0.6648	0.7871	1.4518	480
500	680.9	0.0204	0.6545	0.6749	487.9	714.3	1202.2	0.6890	0.7443	1.4333	500
520	812.5	0.0209	0.5386	0.5596	512.0	687.0	1199.0	0.7133	0.7013	1.4146	520
540	962.8	0.0215	0.4437	0.4651	536.8	657.5	1194.3	0.7378	0.6577	1.3954	540
560	1133.4	0.0221	0.3651	0.3871	562.4	625.3	1187.7	0.7625	0.6132	1.3757	560
580	1326.2	0.0228	0.2994	0.3222	589.1	589.9	1179.0	0.7876	0.5673	1.3550	580
600	1543.2	0.0236	0.2438	0.2675	617.1	550.6	1167.7	0.8134	0.5196	1.3330	600
620	1786.9	0.0247	0.1962	0.2208	646.9	506.3	1153.2	0.8403	0.4689	1.3092	620
640	2059.9	0.0260	0.1543	0.1802	679.1	454.6	1133.7	0.8686	0.4134	1.2821	640
660	2365.7	0.0277	0.1166	0.1443	714.9	392.1	1107.0	0.8995	0.3502	1.2498	660
680	2708.6	0.0304	0.0808	0.1112	754.5	310.1	1068.5	0.9365	0.2720	1.2086	680
700	3094.3	0.0366	0.0396	0.0752	822.4	172.7	995.2	0.9901	0.1490	1.1390	700
705.3	3203.2	0.0308	0	0.0506	906.0	0	906.0	1.0512	0	1.0612	705.3

TABLE 10-2-2
SATURATED STEAM: PRESSURE TABLE

Press. psia	Temp. °F	Volume, ft ³ /lb			Enthalpy, Btu/lb			Entropy, Btu/lb x °F			Energy, Btu/lb		Press. psia
		Water <i>v_f</i>	Evap <i>v_{fg}</i>	Steam <i>v_g</i>	Water <i>h_f</i>	Evap <i>h_{fg}</i>	Steam <i>h_g</i>	Water <i>s_f</i>	Evap <i>s_{fg}</i>	Steam <i>s_g</i>	Water <i>u_f</i>	Steam <i>u_g</i>	
0.0886	32.018	0.01602	3302.4	3302.4	0.00	1075.3	1075.3	0	2.1872	2.1872	0	1021.3	0.0886
0.10	35.023	0.01602	2945.5	2945.5	1.03	1073.8	1076.8	0.0061	2.1705	2.1766	3.03	1022.3	0.10
0.13	45.453	0.01602	2004.7	2004.7	13.50	1067.9	1081.4	0.0271	2.1140	2.1411	13.50	1025.7	0.13
0.20	53.190	0.01603	1526.3	1526.3	21.22	1063.5	1084.7	0.0422	2.0738	2.1160	21.22	1028.3	0.20
0.30	64.484	0.01604	1039.7	1039.7	32.54	1057.1	1089.7	0.0641	2.0168	2.0809	32.54	1032.0	0.30
0.40	72.849	0.01606	792.0	792.1	40.92	1052.4	1093.3	0.0799	1.9782	2.0582	40.92	1034.7	0.40
0.5	79.586	0.01607	641.5	641.5	47.82	1048.6	1096.3	0.0925	1.9446	2.0370	47.82	1036.9	0.5
0.6	85.218	0.01609	540.0	540.1	53.25	1045.5	1098.7	0.1028	1.9136	2.0215	53.24	1038.7	0.6
0.7	90.09	0.01610	466.93	466.94	58.10	1042.7	1100.8	0.3	1.8966	2.0083	58.10	1040.3	0.7
0.8	94.38	0.01611	411.67	411.69	62.39	1040.3	1102.6	0.1117	1.8775	1.9970	62.39	1041.7	0.8
0.9	98.24	0.01612	368.41	368.43	66.24	1038.1	1104.3	0.1264	1.8606	1.9870	66.24	1042.9	0.9
1.0	101.74	0.01614	333.59	333.60	69.73	1036.1	1105.8	0.1325	1.8455	1.9781	69.73	1044.1	1.0
2.0	126.07	0.01623	173.74	173.76	94.03	1022.1	1116.2	0.1750	1.7490	1.9200	94.03	1051.3	2.0
3.0	141.47	0.01630	118.71	118.73	109.42	1013.2	1122.6	0.2009	1.6854	1.8864	109.41	1056.7	3.0
4.0	152.56	0.01636	90.63	90.64	120.92	1006.4	1127.3	0.2199	1.6428	1.8626	120.90	1060.2	4.0
5.0	162.24	0.01641	73.515	73.53	130.20	1000.9	1131.1	0.2349	1.6094	1.8443	130.18	1063.1	5.0
6.0	170.05	0.01645	61.967	61.98	138.03	996.2	1134.2	0.2474	1.5820	1.8294	138.01	1065.4	6.0
7.0	176.84	0.01649	53.634	53.65	144.83	992.1	1136.9	0.2581	1.5587	1.8168	144.81	1067.4	7.0
8.0	182.86	0.01653	47.325	47.35	150.87	988.5	1139.3	0.2676	1.5384	1.8060	150.84	1069.2	8.0
9.0	188.27	0.01656	42.385	42.40	156.30	985.1	1141.4	0.2760	1.5204	1.7964	156.28	1070.8	9.0
10	193.21	0.01659	38.404	38.42	161.26	982.1	1143.3	0.2836	1.5043	1.7879	161.23	1072.3	10
14.696	212.00	0.01672	26.782	26.80	180.17	970.3	1150.5	0.3121	1.4447	1.7568	180.12	1077.8	14.696
15	213.03	0.01673	26.274	26.29	181.21	969.7	1150.9	0.3137	1.4415	1.7552	181.16	1077.9	15
20	227.96	0.01683	20.070	20.087	194.27	960.1	1156.3	0.3358	1.3962	1.7320	194.21	1082.0	20
30	250.34	0.01701	13.7266	13.744	218.9	945.2	1164.1	0.3682	1.3313	1.6995	218.8	1087.9	30
40	267.25	0.01715	10.4794	10.497	236.1	933.6	1169.8	0.3921	1.2844	1.6765	236.0	1092.1	40
50	281.02	0.01727	8.4967	8.514	250.2	923.9	1174.1	0.4112	1.2474	1.6586	250.1	1095.3	50
60	292.71	0.01738	7.1562	7.174	262.2	915.4	1177.6	0.4273	1.2167	1.6440	262.0	1098.0	60
70	302.93	0.01748	6.1875	6.205	272.7	907.8	1180.6	0.4411	1.1903	1.6316	272.5	1100.2	70
80	312.04	0.01757	5.4536	5.471	282.1	900.9	1183.1	0.4534	1.1675	1.6208	281.9	1102.1	80
90	320.28	0.01766	4.8777	4.895	290.7	894.6	1185.3	0.4643	1.1470	1.6113	290.4	1103.7	90
100	327.52	0.01774	4.4133	4.431	298.5	888.6	1187.2	0.4743	1.1284	1.6027	298.2	1105.2	100
120	341.27	0.01789	3.7097	3.728	312.5	877.3	1190.4	0.4919	1.0960	1.5879	312.2	1107.5	120
140	353.04	0.01803	3.2010	3.219	325.0	868.0	1193.0	0.5071	1.0681	1.5752	324.5	1109.6	140
160	363.55	0.01815	2.8155	2.834	336.1	859.0	1195.1	0.5206	1.0435	1.5641	335.5	1111.2	160
180	373.08	0.01827	2.5129	2.531	346.2	850.7	1196.9	0.5328	1.0215	1.5543	345.6	1112.5	180
200	381.80	0.01839	2.2695	2.287	355.5	842.8	1198.3	0.5438	1.0016	1.5454	354.8	1113.7	200
250	400.97	0.01865	1.8245	1.8432	376.1	825.0	1201.1	0.5579	0.9585	1.5264	375.3	1115.8	250
300	417.35	0.01889	1.5238	1.5427	394.0	808.9	1202.9	0.5882	0.9223	1.5105	392.9	1117.2	300
350	431.73	0.01913	1.3064	1.3255	409.8	794.2	1204.0	0.6039	0.8909	1.4968	408.6	1118.1	350
400	444.60	0.0193	1.14162	1.1610	424.2	780.4	1204.6	0.6217	0.8630	1.4847	422.7	1118.7	400
450	456.23	0.0195	1.01224	1.0318	437.3	767.5	1204.8	0.6360	0.8378	1.4738	435.7	1118.9	450
500	467.01	0.0198	0.90787	0.9276	449.5	755.1	1204.7	0.6490	0.8148	1.4639	447.7	1118.8	500
550	476.94	0.0199	0.82183	0.8418	460.9	743.3	1204.3	0.6611	0.7936	1.4547	458.9	1118.5	550
600	486.20	0.0201	0.74962	0.7696	471.7	732.0	1203.7	0.6723	0.7738	1.4461	469.5	1118.2	600
700	503.08	0.0205	0.63505	0.6556	491.5	710.2	1201.8	0.6928	0.7377	1.4304	488.9	1116.9	700
800	518.21	0.0209	0.54809	0.5690	509.8	689.6	1199.4	0.7111	0.7051	1.4163	506.7	1115.2	800
900	531.95	0.0212	0.47968	0.5009	526.7	669.7	1196.4	0.7279	0.6753	1.4032	523.2	1113.0	900
1000	544.58	0.0216	0.42436	0.4460	542.5	650.4	1192.9	0.7434	0.6476	1.3910	538.6	1110.4	1000
1100	556.28	0.0220	0.37863	0.4006	557.5	631.5	1189.1	0.7578	0.6216	1.3794	553.1	1107.5	1100
1200	567.19	0.0223	0.34013	0.3623	571.9	613.0	1184.8	0.7714	0.5969	1.3683	566.9	1104.3	1200
1300	577.42	0.0227	0.30722	0.3299	585.6	594.6	1180.2	0.7843	0.5733	1.3577	580.1	1100.9	1300
1400	587.07	0.0231	0.27871	0.3018	598.8	576.3	1175.3	0.7966	0.5507	1.3474	592.9	1097.1	1400
1500	596.20	0.0235	0.25372	0.2772	611.7	558.4	1170.1	0.8085	0.5288	1.3373	605.2	1093.1	1500
2000	635.80	0.0257	0.16296	0.1863	672.1	466.2	1138.3	0.8625	0.4256	1.2881	662.6	1068.6	2000
2500	668.11	0.0286	0.10209	0.1307	731.7	361.6	1093.3	0.9139	0.3206	1.2345	718.5	1032.9	2500
3000	699.33	0.0343	0.05073	0.0850	801.3	218.4	1020.3	0.9728	0.1891	1.1619	782.8	973.1	3000
3208.2	705.47	0.0308	0	0.0508	906.0	0	906.0	1.0612	0	1.0612	875.9	375.9	3208.2

TABLE 10-2-3
SUPERHEATED STEAM

Abs. press. lb/sq in. (sat. temp.)		Temperature, °F														
		100	200	300	400	500	600	700	800	900	1000	1100	1200	1300	1400	1500
1 (101.74)	v	0.0161	292.5	452.3	511.9	571.5	631.3	690.7								
	h	68.00	1150.2	1195.7	1241.8	1288.2	1335.9	1384.3	1433.6	1483.7	1534.7	1586.7	1639.6	1693.3	1748.0	1803.5
	s	0.1295	2.0509	2.1152	2.1722	2.2237	2.2708	2.3144								
5 (162.24)	v	0.0161	78.14	90.24	102.24	114.21	126.15	138.08	150.01	161.94	173.86	185.78	197.70	209.62	221.53	233.45
	h	68.01	1148.6	1194.8	1241.3	1288.2	1335.9	1384.3	1433.6	1483.7	1534.7	1586.7	1639.6	1693.3	1748.0	1803.5
	s	0.1295	1.8716	1.9369	1.9943	2.0460	2.0932	2.1369	2.1776	2.2159	2.2521	2.2864	2.3194	2.3509	2.3811	2.4101
10 (193.21)	v	0.0161	38.84	44.98	51.03	57.04	63.03	69.00	74.98	80.94	86.91	92.87	98.84	104.80	110.76	116.72
	h	68.02	1146.6	1193.7	1240.6	1287.5	1335.5	1384.0	1433.4	1483.5	1534.6	1586.6	1639.5	1693.2	1747.9	1803.4
	s	0.1295	1.7928	1.8593	1.9173	1.9692	2.0166	2.0603	2.1011	2.1394	2.1757	2.2101	2.2430	2.2744	2.3048	2.3337
15 (213.23)	v	0.0161	0.0166	29.899	33.963	37.985	41.966	45.978	49.964	53.945	57.926	61.905	65.882	69.858	73.833	77.807
	h	68.04	168.09	1152.5	1235.9	1287.3	1335.2	1383.4	1432.2	1483.4	1534.5	1586.5	1639.4	1693.2	1747.8	1803.4
	s	0.1295	0.2940	1.8134	1.8720	1.9242	1.9717	2.0155	2.0563	2.0946	2.1309	2.1653	2.1982	2.2299	2.2599	2.2890
20 (227.96)	v	0.0161	0.0166	22.354	25.428	28.457	31.466	34.465	37.458	40.447	43.435	46.420	49.405	52.388	55.370	58.352
	h	68.05	168.11	1191.4	1239.2	1286.9	1334.9	1383.5	1432.9	1483.2	1534.3	1586.3	1639.3	1693.1	1747.8	1803.3
	s	0.1295	0.2940	1.7805	1.8397	1.8921	1.9397	1.9836	2.0244	2.0628	2.0991	2.1336	2.1665	2.1979	2.2282	2.2572
30 (267.25)	v	0.0161	0.0166	11.036	12.824	14.165	15.685	17.195	18.699	20.199	21.697	23.194	24.689	26.183	27.676	29.168
	h	68.10	168.15	1186.6	1236.4	1285.0	1333.6	1382.5	1432.1	1482.5	1533.7	1585.7	1638.6	1692.7	1747.5	1803.0
	s	0.1295	0.2940	1.6992	1.7608	1.8143	1.8624	1.9068	1.9476	1.9860	2.0224	2.0569	2.0899	2.1224	2.1546	2.1867
40 (292.71)	v	0.0161	0.0166	7.257	8.354	9.400	10.425	11.438	12.446	13.450	14.452	15.452	16.450	17.448	18.445	19.441
	h	68.15	168.20	1181.6	1231.5	1280.2	1328.8	1377.3	1426.1	1475.3	1525.2	1575.9	1626.4	1677.4	1728.5	1779.6
	s	0.1295	0.2939	1.6492	1.7134	1.7681	1.8168	1.8612	1.9024	1.9410	1.9774	2.0120	2.0450	2.0765	2.1068	2.1359
50 (312.04)	v	0.0161	0.0166	0.0173	6.218	7.018	7.794	8.560	9.319	10.075	10.829	11.581	12.331	13.081	13.829	14.577
	h	68.21	168.24	269.74	1220.5	1291.3	1330.9	1380.5	1430.5	1481.1	1532.6	1584.9	1638.0	1692.0	1746.8	1802.5
	s	0.1295	0.2939	0.4371	1.6790	1.7349	1.7842	1.8289	1.8702	1.9089	1.9454	1.9800	2.0131	2.0446	2.0750	2.1041
60 (327.42)	v	0.0161	0.0166	0.0173	4.935	5.588	6.216	6.833	7.443	8.050	8.655	9.258	9.860	10.460	11.060	11.659
	h	68.26	168.29	269.77	1227.4	1279.3	1329.6	1379.5	1429.7	1480.4	1532.0	1584.4	1637.6	1691.6	1746.5	1802.2
	s	0.1295	0.2939	0.4371	1.6516	1.7088	1.7586	1.8036	1.8451	1.8839	1.9208	1.9552	1.9883	2.0199	2.0502	2.0794
70 (341.27)	v	0.0161	0.0166	0.0173	4.0786	4.6341	5.1637	5.6831	6.1928	6.7006	7.2060	7.7094	8.2119	8.7130	9.2134	9.7130
	h	68.31	168.33	259.81	1224.1	1277.4	1328.1	1378.4	1428.8	1479.5	1531.4	1583.9	1637.1	1691.3	1746.2	1802.0
	s	0.1295	0.2939	0.4371	1.6286	1.6872	1.7376	1.7829	1.8246	1.8635	1.9001	1.9349	1.9680	1.9996	2.0300	2.0592
80 (353.04)	v	0.0161	0.0166	0.0173	3.4661	3.9526	4.4119	4.8585	5.2998	5.7364	6.1709	6.6036	7.0349	7.4652	7.8948	8.3233
	h	68.37	168.38	269.83	1220.8	1275.3	1326.8	1377.4	1428.0	1479.1	1530.8	1583.4	1636.7	1690.9	1745.9	1801.7
	s	0.1295	0.2939	0.4373	1.6085	1.6686	1.7196	1.7652	1.8071	1.8461	1.8823	1.9176	1.9508	1.9823	2.0129	2.0421
90 (363.55)	v	0.0161	0.0166	0.0173	3.0060	3.4413	3.8480	4.2420	4.6295	5.0132	5.3945	5.7741	6.1522	6.5293	6.9055	7.2811
	h	68.42	168.42	269.89	1217.4	1273.3	1325.4	1376.4	1427.2	1478.4	1530.3	1582.9	1636.3	1690.5	1745.6	1801.4
	s	0.1294	0.2938	0.4370	1.5906	1.6522	1.7039	1.7499	1.7919	1.8310	1.8678	1.9027	1.9359	1.9676	1.9980	2.0273
100 (373.08)	v	0.0161	0.0166	0.0174	2.6474	3.0433	3.4093	3.7621	4.1084	4.4505	4.7907	5.1289	5.4657	5.8014	6.1363	6.4704
	h	68.47	168.47	269.92	1213.8	1271.2	1324.0	1375.3	1426.3	1477.7	1529.7	1582.4	1635.9	1690.2	1745.3	1801.2
	s	0.1294	0.2938	0.4370	1.5743	1.6376	1.6900	1.7362	1.7784	1.8176	1.8545	1.8894	1.9227	1.9545	1.9849	2.0142
120 (381.80)	v	0.0161	0.0166	0.0174	2.3590	2.7247	3.0533	3.3783	3.6915	4.0008	4.3077	4.6128	4.9165	5.2191	5.5209	5.8219
	h	68.52	168.51	269.96	1210.1	1269.0	1322.6	1374.3	1425.5	1477.0	1529.1	1581.9	1635.4	1689.8	1745.0	1800.9
	s	0.1294	0.2938	0.4369	1.5593	1.6242	1.6776	1.7239	1.7663	1.8057	1.8426	1.8776	1.9109	1.9427	1.9732	2.0025
130 (400.97)	v	0.0161	0.0166	0.0174	0.0186	2.1504	2.4662	2.8872	3.3109	3.7369	4.1648	4.5945	5.0259	5.4589	5.8934	6.3294
	h	68.56	168.56	270.05	1206.5	1265.5	1319.0	1371.6	1424.3	1477.3	1530.6	1584.4	1638.7	1693.4	1748.8	1804.9
	s	0.1294	0.2937	0.4368	1.5467	1.5951	1.6502	1.6976	1.7405	1.7801	1.8173	1.8524	1.8858	1.9177	1.9482	1.9776
140 (417.35)	v	0.0161	0.0166	0.0174	0.0186	1.7668	2.0044	2.2263	2.4407	2.6509	2.8585	3.0643	3.2688	3.4721	3.6746	3.8764
	h	68.59	168.59	270.14	1203.1	1262.1	1315.7	1368.9	1422.3	1476.1	1530.2	1584.6	1639.4	1694.6	1750.3	1806.6
	s	0.1294	0.2937	0.4367	1.5308	1.5703	1.6274	1.6758	1.7192	1.7591	1.7964	1.8317	1.8652	1.8972	1.9278	1.9572
150 (431.73)	v	0.0161	0.0166	0.0174	0.0186	1.4913	1.7028	1.8970	2.0832	2.2652	2.4445	2.6219	2.7980	2.9730	3.1471	3.3205
	h	68.62	168.62	270.24	1200.0	1259.0	1312.6	1365.8	1419.2	1473.0	1527.1	1581.5	1636.3	1691.5	1747.2	1803.5
	s	0.1293	0.2936	0.4367	1.5164	1.5483	1.5777	1.6057	1.6323	1.6578	1.6823	1.7058	1.7283	1.7498	1.7703	1.7900
160 (444.60)	v	0.0161	0.0166	0.0174	0.0186	1.2841	1.4763	1.6499	1.8131	1.9759	2.1389	2.2991	2.4540	2.5987	2.7515	2.9037
	h	68.65	168.65	270.33	1196.5	1255.5	1309.1	1362.4	1415.9	1470.0	1524.3	1579.0	1634.0	1689.3	1745.0	1799.9
	s	0.1293	0.2935	0.4366	1.5022	1.5292	1.5501	1.5650	1.5850	1.6032	1.6203	1.6368	1.6525	1.6677	1.6825	1.6970
180 (467.01)	v	0.0161	0.0166	0.0174	0.0186	0.9919	1.1584	1.3037	1.4397	1.5708	1.6992	1.8256	1.9507	2.0748	2.1977	2.3200
	h	68.72	168.72	270.41	1193.0	1252.0	1305.6	1358.9	1412.7	1467.0	1521.7	1576.8	1632.2	1687.9	1744.0	1799.9
	s	0.1292	0.2934	0.4364	1.4881	1.5112	1.5291	1.5423	1.5578	1.5708	1.5837	1.5968	1.6098	1.6228	1.6358	1.6488

THERMODYNAMIC CYCLES

Two cycles should be noted.

CARNOT CYCLE

The most efficient cycle, which serves as the basis for comparison of all cycles, is the Carnot cycle. It consists of four reversible ideal processes (Figure 10-2-6): 1) the

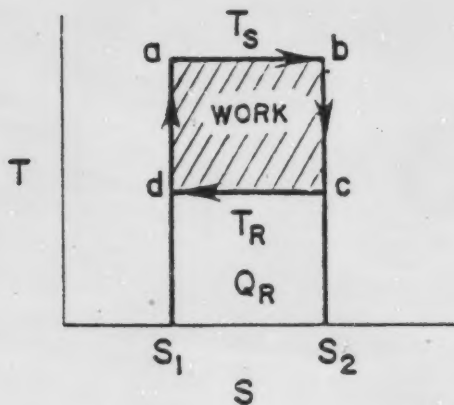


Figure 10-2-6.
Temperature-entropy (T-S)
diagram, Carnot cycle.

isothermal (constant temperature) heat addition from a to b, 2) an isentropic (constant entropy) expansion from b to c, 3) an isothermal heat rejection from c to d, and 4) an isentropic compression from d to a.

RANKINE CYCLE

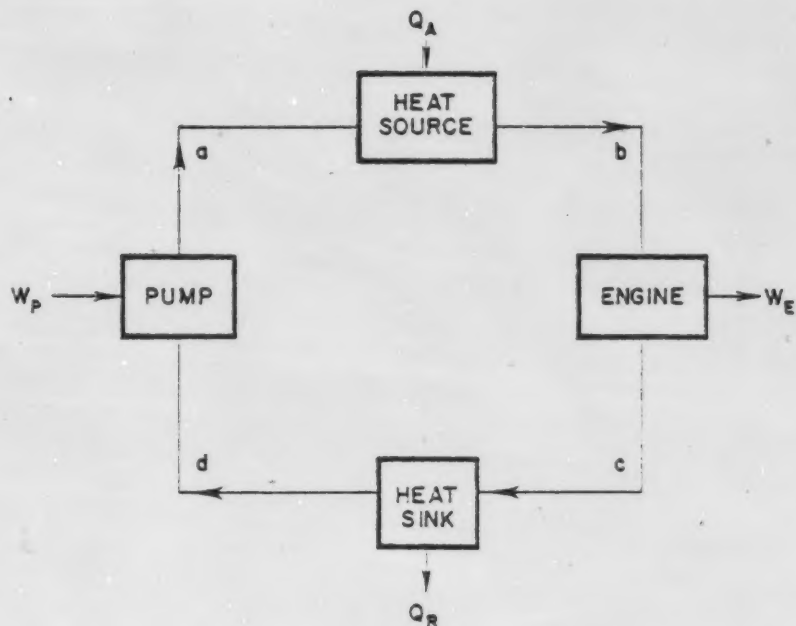
In practical power plant applications, the Rankine cy-

cle is used. In this cycle, all energy in the steam entering the turbine cannot be converted into useful work. The thermal efficiency of a work-producing cycle is the output divided by the input (Figure 10-2-7):

$$E = \frac{\text{output}}{\text{input}} = \frac{W_{\text{engine}} - W_{\text{pump}}}{Q_A} = \frac{Q_A - Q_R}{Q_A}$$

Eq. 10-2-4

Figure 10-2-7.
Elements of a
thermodynamic
system.



Note that output may be expressed as the net amount of work done or as the difference between heat added and heat rejected.

In a simplified flow diagram of the main steam cycle

(Figure 10-2-8) of a steam power plant, points 1, 2, 3 and 4

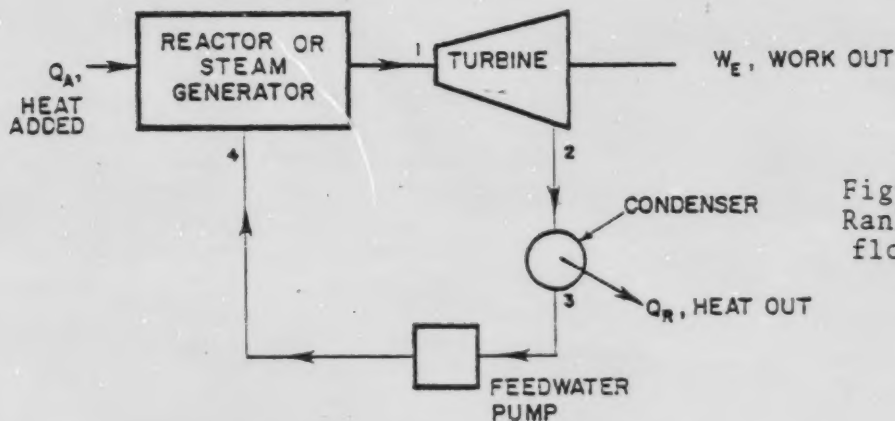


Figure 10-2-8.
Rankine cycle,
flow diagram.

show the flow entering or leaving different parts of the system. These points show (Figure 10-2-9) the relationship between temperature and entropy in each process.

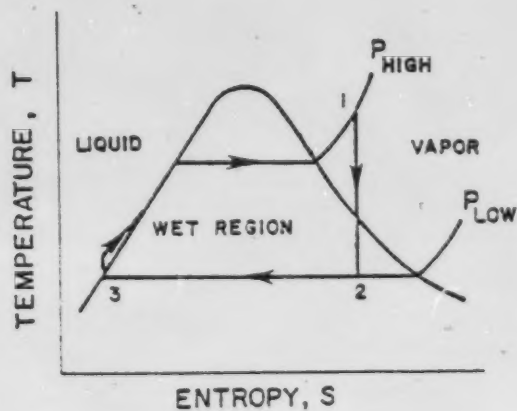


Figure 10-2-9.
Rankine cycle,
T-S diagram.

Point 1 represents the stage at which superheated steam from the boiler enters the turbine, where it does work to

turn the generator. In the turbine, steam expands and cools to point 2. At this point, steam enters the condenser where cooling water condenses the steam. The condensate (liquid water) then leaves the condenser at point 3, and is then pumped to a boiler and pressurized at point 4 to be recycled into the system.

The term carryover is used in conjunction with quality and is defined as the weight fraction of water in the steam-water mixture:

$$\text{Carryover} = 1 - \text{quality.} \qquad \text{Eq. 10-2-5}$$

Typical PWR steam generator performance specifications limit carryover of steam leaving the unit to 0.25%, or 0.25 lbs in a 100-lb mixture.

FACTORS AFFECTING EFFICIENCY AND CYCLE DIAGRAMS

Thermal efficiency depends primarily on the temperature at which heat is added and rejected. It has always been the objective of efficient power plant operation to maximize the proportion of energy available for conversion to useful work, which is done by increasing steam temperature and pressure, and by lowering condenser pressure (using the heat sink with the lowest available temperature).

REGENERATIVE HEATING

Thermal efficiency of a steam cycle may also be increased by heating feedwater prior to its entrance to the steam generator (Figure 10-2-10). After partial expansion

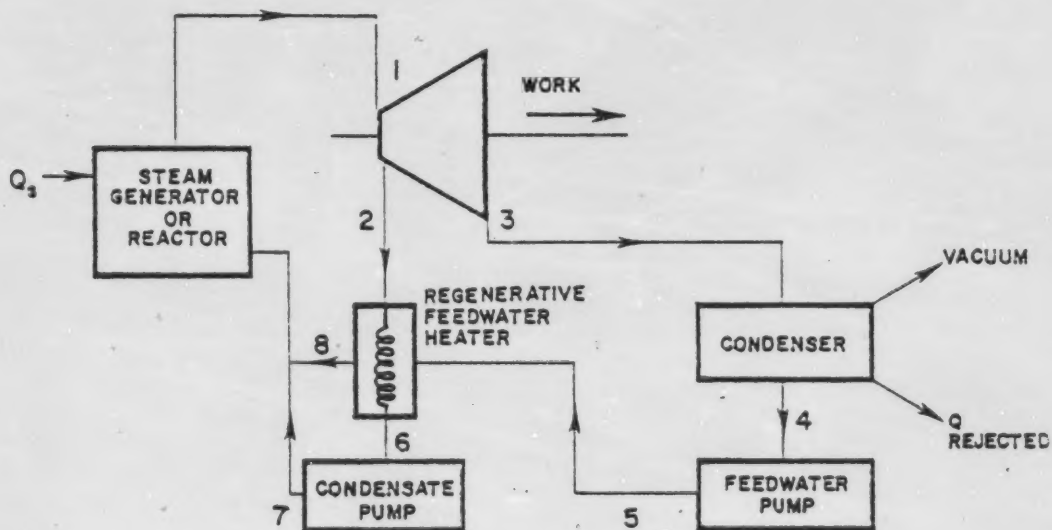


Figure 10-2-10. Regenerative feedwater-heating cycle.

in the turbine, some steam is extracted (point 2) and supplied to a feedwater heater. The remainder of the steam finishes its expansion in the turbine and passes to the condenser. The resulting condensate, pumped through the heater, is heated to the temperature of the condensing steam. In an ideal case, condensate formed in the heater is removed at condensing temperature and pumped into the feedwater line. In practice, however, this feedwater pump is eliminated to ensure greater reliability of operation, and the condensate flows to the condenser.

RESUPERHEATING (REHEATING) CYCLE

To prevent excess moisture formation in the steam, it is only partially expanded in the high-pressure part of the turbine, through a moisture separator (Figures 10-2-1 and 10-2-2), and then is piped back to the steam generator where it is reheated to a temperature near the temperature of the steam entering the high-pressure turbine. This steam is then returned to the turbine room and enters the low-pressure part of the turbine.

HEAT BALANCE

In nuclear power plants, a heat balance provides power calibration of the reactor and enables optimization of efficiency in the plant. Calculation of a total heat balance for such a system (Figure 10-2-11) is left to class participation; however, to ensure sufficient instruction in the heat balance principles, two sample calculations are offered.

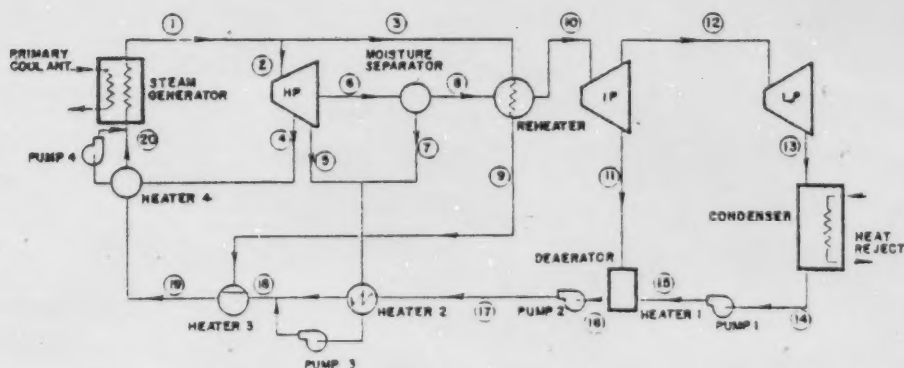


Figure 10-2-11. Typical PWR power cycle.

EXAMPLE 1

Given: An oversimplified BWR as a heat source with measured feedwater, flow, temperature and steam properties as follows:

Feed flow = steam flow = $4.0 \times 10^6 \text{ lb}_m/\text{hr}$.

Feed temperature = 232°F .

Steam = 1000 psia, 0% moisture.

Find: Reactor output in MWt (use Figure 10-2-8 as a reference).

$$\begin{aligned}\text{Thermal power} &= (\text{mass flow rate}) \times \\ &\quad \left(\frac{\text{enthalpy out}}{\text{steam}} - \frac{\text{enthalpy in}}{\text{feedwater}} \right) \\ &= m (h_{\text{out}} - h_{\text{in}}).\end{aligned}$$

From the steam tables, feedwater enthalpy at 232°F is 200.25 Btu/lb_m and steam enthalpy is 1157.7 Btu/lb_m .

Therefore, thermal power

$$\begin{aligned}&= 4.0 \times 10^6 \text{ lb}_m/\text{hr} (1157.7 - 200.25) \text{ Btu/lb}_m \\ &= 3.97 \times 10^9 \text{ Btu/hr} \\ &= 1164 \text{ MWt}.\end{aligned}$$

EXAMPLE 2

Given: Turbine in Example 1, where steam flow to turbine equals feedwater flow; h_{in} is 1192.9 Btu/lb ; steam out of turbine (h_{out}) is 1050 Btu/lb .

Find: Turbine output in MW:

Mechanical power

$$\begin{aligned} &= (\text{mass flow rate}) \times (\text{change in enthalpy}) \\ &= 4 \times 10^6 \text{ lb}_m/\text{hr} (1192.6 - 1050) \text{ Btu/lb} \\ &= 5.7 \times 10^8 \text{ Btu/hr} \\ &= 167 \text{ MW} = 224,000 \text{ hp.} \end{aligned}$$

Effects on efficiency, such as moisture carryover, superheat, subcooled condensate and feedwater heating may be analyzed in a manner similar to the previous examples. The results will show that, to maximize plant efficiency, it is necessary to maximize superheat (if available), minimize carryover, decrease condensate subcooling and maintain feedwater heating at its maximum. Remember there must be sufficient condensate subcooling to prevent the water from flashing to steam when it is pumped.

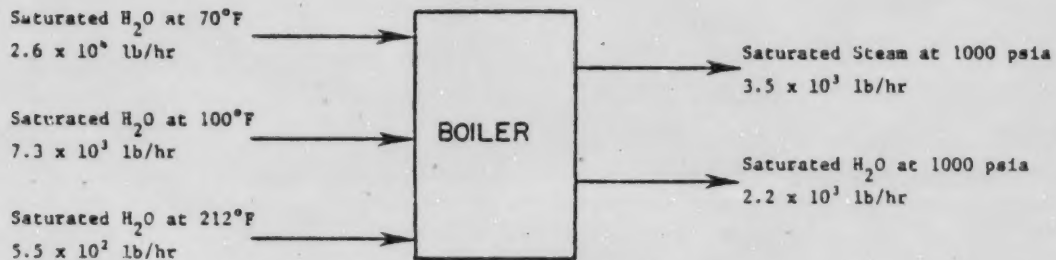


EXERCISES

1. If $h_{fg} = 1000 \text{ Btu/lb}_m$ at 14.7 psia, how much heat is required to convert 200 pounds of water at 0 psig and 100°F to steam at atmospheric pressure?
2. If specific heat of steam is $0.5 \text{ Btu/lb}_m \cdot ^\circ\text{F}$, how much more heat is required to make the steam in Exercise 1 superheated steam at 262°F?
3. What is the enthalpy of steam at 1000 psia and 800°F? At a saturated condition?
4. Given a PWR operating at a flow of 80.1 lb/hr, 2300

psia, and with inlet and outlet temperatures of 547°F and 609°F respectively, determine thermal rating of the plant, assuming three primary pumps of 4000 hp that operate at 80% efficiency.

5. What power is produced in the boiler shown?



6. What are the units of efficiency, quality and carry-over?
7. Use Figure 10-2-11 and the steam table. Given: a heat-transfer rate of 4×10^9 Btu/hr; for HP turbine; steam 2 is 1000 psia and 580°F, steam 4 is 500 psia, and steam 5 and 6 is 200 psia. Find: h_2 , s_2 , h_4 , $(h_2 - h_4)$ isentropic, $(h_2 - h_4)$ actual, h_4 actual, h_5 , $(h_2 - h_5)$ isentropic, $(h_2 - h_5)$ actual, h_5 actual and % moisture at 5 and 6.
8. In an auxiliary water cooling system, flow through the tube side of a heat exchanger is 500 gal/min with a temperature rise of 14.0°F. Temperature rise on shell side is 10°F. Find: Flow rate in shell side of system.



Locate a steam power plant, preferably nuclear, near the institution, that can accomodate class visits on a reasonably frequent basis - namely at the beginning of Course 10, "Power Plant Systems," and toward the latter part of this module.

For the class, components and process instrumentation used in the heat balance at the plant should be identified in advance by instructor or plant personnel. Prepare a schematic diagram (similar to Figure 10-2-11); list components and instruments, and outline a format for conducting a heat-balance analysis of the plant.



PROCEDURES

The following procedural outline is suggested for power plant heat-balance analysis:

1. Instructor and students study steam cycle of chosen plant prior to visit.
2. Obtain advance data on plant, including components, flow rates, temperatures and pressure of cycle.
3. Work through a simplified heat balance in class prior to visit.
4. Establish data form for heat-balance analysis at plant before visit.
5. On site, after steady-state power output has been maintained for at least one-half hour, take data (on in-

- structions from plant operators), including MWe output.
6. In classroom, analyze data, summarize results and write report answering the following questions:

What is thermal efficiency of this plant compared to the national average?

What would be expected efficiency if condenser inlet water were 30°F cooler (as in winter)?

What was percent of error of heat balance compared to plant's determination?



DATA TABLE

Students to develop data tables for heat-balance data acquisition, based on above procedure.



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Keenan, J.H. and Keyes, F.G. Thermodynamic Properties of Steam. New York: John Wiley and Sons, Inc., 1967.

Meyer, C.A. and others. Thermodynamic and Transport Properties of Steam. New York: American Society of Mechanical Engineers, 1967.



1. Define the following terms and give appropriate units where applicable:

Energy.

Work.

Flow work.

Heat. .

Thermodynamics.

First Law of Thermodynamics (describe).

Second Law of Thermodynamics (describe).

Properties.

Enthalpy.

Latent heat of vaporization.

Entropy.

Specific heat.

Specific volume.

Saturation temperature.

Superheated.

Carnot cycle (describe).

Rankine cycle (describe).

Thermal efficiency.

Saturated liquid.

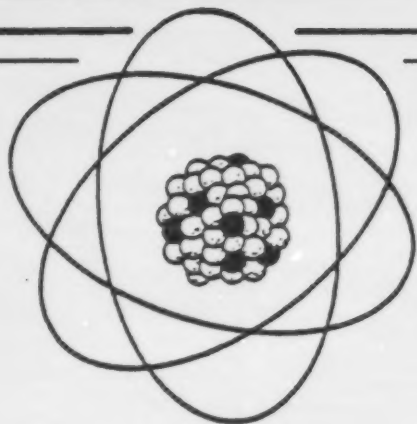
Saturated vapor.

Carryover.

Heat balance.

2. Identify three different types of energy as discussed in this module:
 - (1)
 - (2)
 - (3)
3. List the two major thermodynamic cycles and different portions of cycles (such as reheat-regeneration cycles in particular); highlight basic cycle differences between nuclear-fueled and fossil-fueled systems.
4. Sketch, on a separate sheet, a typical steam-cycle diagram and a T-S diagram; reference typical steam conditions:
5. Given five steam pressures and five steam temperatures by instructor, use steam tables from this module to find the entropy and enthalpy of steam/liquid conditions:

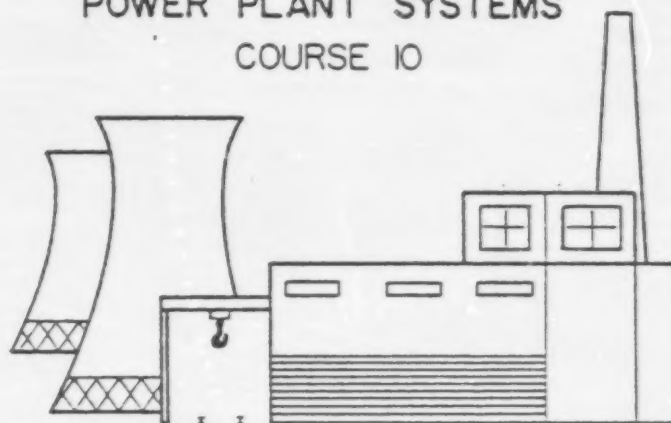
- 70



NUCLEAR TECHNOLOGY

MODULE 10-3 TURBINES AND GENERATORS

POWER PLANT SYSTEMS
COURSE 10



TEC -SW

TECHNICAL EDUCATION RESEARCH CENTER — SOUTHWEST

4201 LAKE SHORE DRIVE WACO, TEXAS



COURSE MODULES

COURSE 10 POWER PLANT SYSTEMS



MODULE 10-1	Power Plant Fundamentals
MODULE 10-2	Power Plant Thermal Cycles
MODULE 10-3	Turbines and Generators
MODULE 10-4	Heat Exchangers and Condensers
MODULE 10-5	Pumps
MODULE 10-6	Valves and Piping
MODULE 10-7	Electrical Transmission and Distribution Systems
MODULE 10-8	Power Plant Fundamentals (Fossil-Fuel Energy Efficiency)
MODULE 10-9	Fossil Plant: Auxiliary Discussions

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Technical Education Research Center
Southwest
4201 Lake Shore Drive, Suite 111
Waco, Texas 76710



Any power plant revolves around its turbine-generator combination - all else is auxiliary to this tandem system. Thus, an operator's or technician's knowledge of these two units may be indicative of his or her technical competence. The ability to maintain stable turbine-generator performance will be apparent throughout an electrical system due to its influence upon all users within a plant's distribution network as well as other power plants within a system's network.

For these reasons, every operator or technician should develop an intimate knowledge of turbines and generators, tentatively to the extent presented in this module, enroute to becoming familiar with overall nuclear power plant design and function.

This module covers major turbine classifications and construction features, generator types and components, and general operating and maintenance procedures and peculiarities of both. Also, applicable auxiliary equipment and systems are introduced.

Finally, review exercises, laboratory procedures (with a list of necessary materials), data tables, and a test designed to determine overall comprehension (of material presented in this module) ensure achievement of the module objectives.



MODULE PREREQUISITES

To meet the objectives of this module, student should have completed a basic course in electricity and electronics, a basic course in mechanics and heat transfer, a course in process instrumentation, a course in metallurgy and metals properties, and Module 10-1, "Power Plant Fundamentals."



OBJECTIVES

Upon completion of this module, the student should be able to:

1. Define and classify the basic types of steam turbines found in nuclear-fueled power generating plants, and describe the operating principles of each.
2. Describe major mechanical components, control systems, auxiliary systems and protection, and safety devices and systems of a typical steam turbine.
3. Identify various types of supervisory instruments necessary for turbine control.
4. Discuss turbine operating procedures and prescribe general turbine maintenance requirements.
5. Define and classify basic types of generators used to generate electricity in a nuclear-fueled power plant.
6. Describe major mechanical components of a typical generator.
7. Identify various auxiliary systems and components associated with a typical generator, including instru-

mentation.

8. Discuss generator operating procedures and prescribe general generator maintenance.



TURBINES

Turbine use in power generation enjoys a long and successful history - from the earliest coal-fueled plants through modern nuclear reactor installations.

TURBINE DEFINITION AND CLASSIFICATION

A typical nuclear power plant steam-driven turbine is shown in Figure 10-3-1. This cutaway view indicates

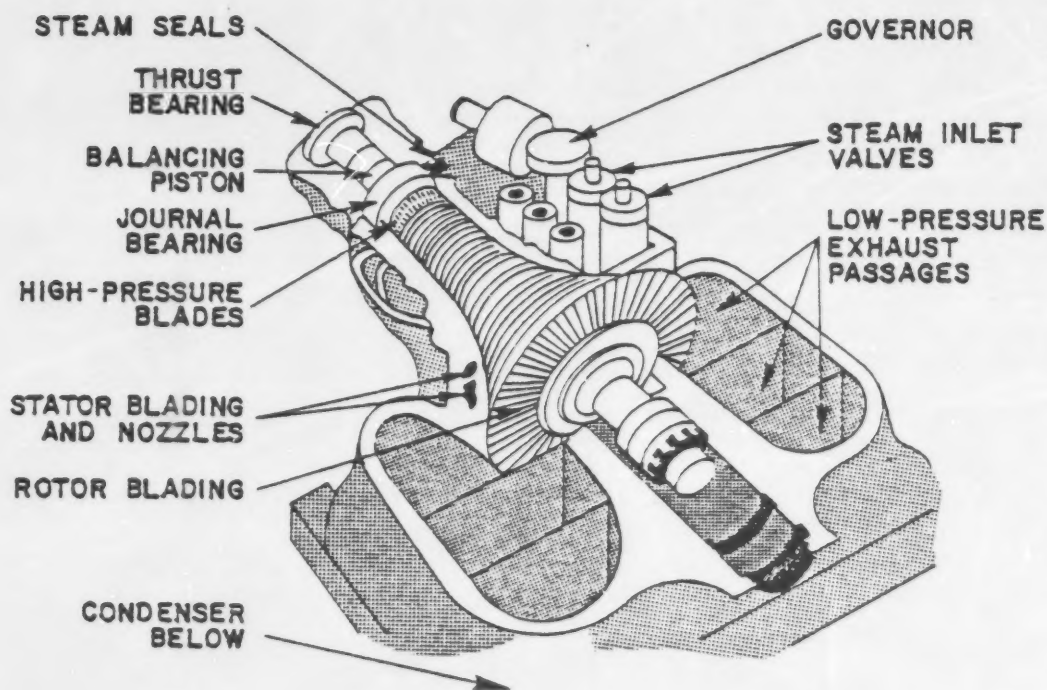


Figure 10-3-1. Cutaway view, steam turbine and condenser.

the major components of a turbine discussed in this module. Not all plants, however, use the exact configuration shown. Therefore, variations in the design and utilization of components and auxiliary equipment and systems are treated briefly.

A turbine is a device that converts potential energy (steam or combustion gases) into useful work according to the following scheme: first, available heat energy is converted to kinetic energy (motion) by expansion of high velocity steam or gas; then, the kinetic energy is converted to mechanical energy (useful work) as the steam or gas jet reacts against blades mounted on a rotating shaft (Figure 10-3-2) or by reaction of the jet expanding in rotating passages (Figure 10-3-3).

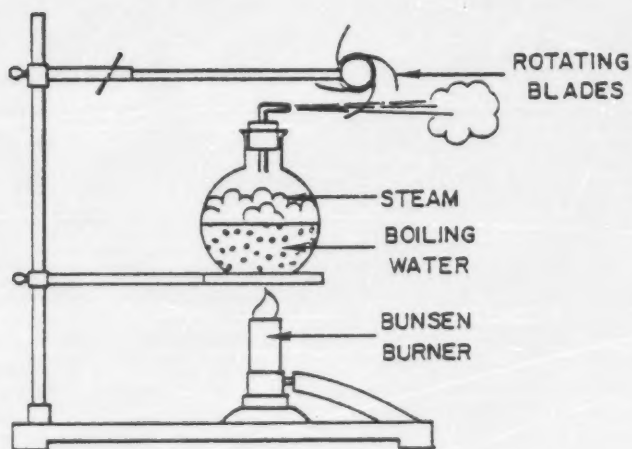
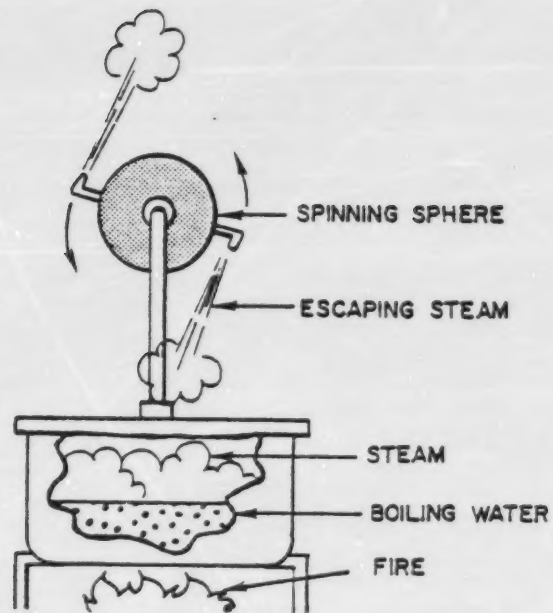


Figure 10-3-2.
Laboratory model
of impulse turbine.

Such steam-operated turbines - commonplace in power generating plants - may be further classified in various other ways, including:

Figure 10-3-3.
Hero's engine - the first
steam turbine - used
reaction principle.



Steam flow direction (relative to rotor).
Steam flow pattern (relative to sequence).
Drive shaft connecting mechanism.
Application.

Steam Flow Direction (Relative to Rotor)

Steam flow may be axially, radially or tangentially related to the rotor.

Axial. This flow pattern - the most commonly used - provides steam flow parallel to the shaft axis as steam passes from inlet to exhaust.

Radial. Steam flows outward from shaft, through blades. Because applications of this design are limited to non-power plant uses, it requires no further discussion for this Course.

Tangential. Steam enters through nozzles positioned to cause steam to strike the rotor blades at a tangent to the periphery of the wheel.

Steam Flow Direction (Relative to Sequence)

Two common designs, single-flow and dual-flow require brief identification.

Single-flow. In this simple design, in which the turbine has a single casing, steam enters at one end, flows through the various stages and exhausts at the other end, fully expanded. It may exhaust into another turbine section, into a condenser or to the atmosphere.

Dual-flow. In this slightly more complex arrangement, steam enters at the center of the casing and flows axially in both directions through separate sets of blading, then exhausts as described above.

Note: Turbines in which steam expands through two or more individual casings are referred to as "compounded" turbines.

Drive-Shaft Connections

Two drive arrangements prevail: in one, the turbine shaft is coupled directly to the equipment to be driven, such as the power generator; in the other arrangement, coupling occurs through a gear box, usually an assembly of reduction gears which provides greater drive stability, but at a lower generator rpm (revolutions per minute).

Application

Turbines come in many sizes and operate through a wide range of speeds to drive a variety of pumps, compressors and other kinds of equipment, in addition to generators. Turbines used in electric power generation are designed to operate at 1.5-in Hg absolute at the exhaust end. (The reason for operating with a vacuum at the exhaust is to increase overall efficiency, as explained in a previous module.)

Turbine-generator units, available in sizes exceeding 1000 Mw, range from single-casing units to multi-casing, compounded, multi-flow reheat units (Figure 10-3-4). The rotational

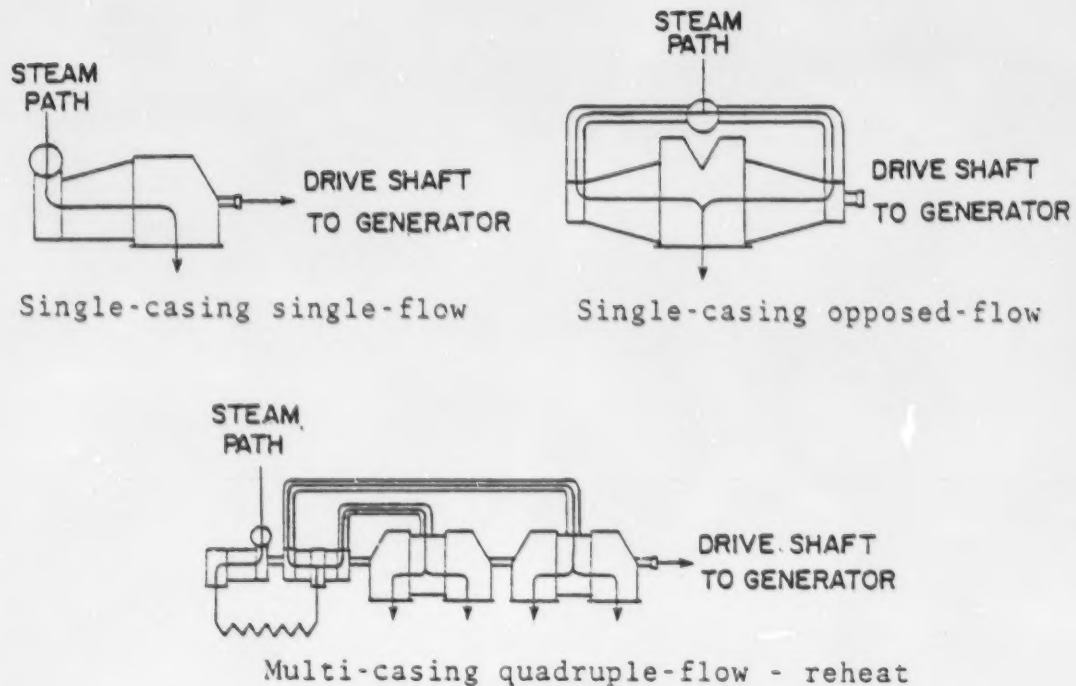


Figure 10-3-4. Basic turbine designs.

speed requirements of these turbines, dictated by the standard 60-Hz frequency of alternating current, result in operation at either 3600 or 1800 rpm.

Steam Expansion

Turbine classification according to steam expansion falls into three categories, determined by turbine blade (or "bucket") design.

Impulse. This design allows steam to expand in the

nozzles, thereby decreasing in pressure but increasing in velocity before striking the rotor blades. As the high velocity jets impinge against and move the blades, which are mounted on a rotatable shaft, kinetic energy becomes mechanical work. Note: Expansion of steam as it flows through the blading is not a contributing factor.

A simple, single-stage impulse turbine consists of one or more nozzles and a single row of rotating blades. A stage, by definition, is that part of a turbine in which a single pressure (or velocity) drop occurs, and usually consists of one row of nozzles and one row of moving blades, or a row of stationary blades and a following row of moving blades.

"Velocity compounding" implies two or more rows of moving blades activated by a single pressure stage. Stationary blades, positioned between the rows of moving blades, reverse direction of steam from row to row (Figure 10-3-5).

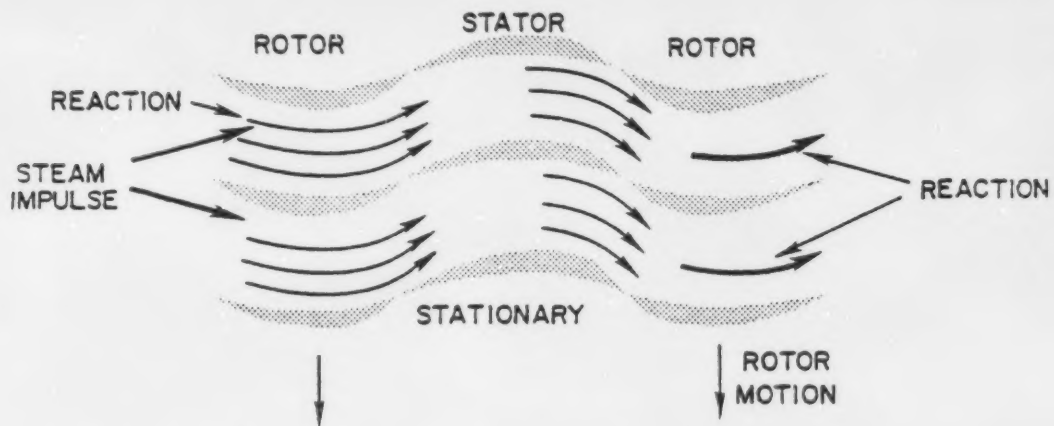


Figure 10-3-5. Turbine "bucket" arrangement - both impulse and reaction forces influence rotor motion. (Note: Stator blades redirect steam so that it impinges next set of rotor blades at proper angle.)

"Pressure compounding" means several single stages mounted on one shaft. The partial expansion of steam and resulting pressure drop that occurs in the first stage is repeated in as many stages as needed to fully expand the steam to its designed exhaust pressure. As the steam expands through the turbine, the nozzles and blading must be enlarged to handle the increased volume of steam.

Reaction. In this design, both the moving and the stationary blades act as nozzles; that is, the steam expands and drops in pressure as it passes through both the moving and stationary blades. The stationary blades direct steam into the rotating blades where it expands to cause a "kick-back" effect that produces mechanical work.

Blades in the first stage are relatively short and narrow, but increase in length and width toward the outlet to accommodate steam expansion and volume increase as it advances toward the exhaust ports.

Combinations. Most large turbines combine the two design features: impulse and reaction. A velocity-compounded stage at the high-pressure inlet may be followed by several reaction stages.

TURBINE CONSTRUCTION

High pressure, superheated steam entering a turbine at velocities exceeding 1000 mph provides unique design and construction problems. For instance, tip speed on the final rotor stage may exceed 700 mph; meanwhile, the steam at this point has begun to condense, which means the rotor blades are striking water droplets at or near the speed of sound. Without a special steel that can resist such erosive action at high temperatures, the blades would quickly wear away. Furthermore, the larger blades are subject to centrifugal

forces up to 90,000 pounds.

Rotors must be statically and dynamically balanced, with factory tolerances on all parts held to within 0.001 in. Special oils developed to withstand the high temperatures, oil cooling systems, and highly reliable pumps provide constant, positive lubrication.

A 3600-rpm, tandem-compounded, triple-flow, reheat turbine (Figure 10-3-1), which is typical of modern installations, consists of 1) one or more rotors, 2) buckets or blading mounted on the rotors, 3) shaft support bearings, 4) rotor casings, which house the revolving rotors, 5) nozzles and stationary blades (through which steam is directed or expanded), 6) rotor seals, 7) steam-admission valves and other devices necessary for proper turbine operation.

A rotor is machined from a steel forging - either a single solid forging or several smaller built-up forgings. Built-up forgings generally satisfy requirements for small or slow-speed rotors. Large, or high-speed systems require solid forged rotors. Also, a rotor used in low-temperature steam applications may be made from carbon steel. But the steel must be alloyed when steam temperatures in excess of 800°F are encountered.

Blades made from corrosion-resisting steel bar stock or cold-rolled drawn stock come in many blade design variations, with several methods of fastening blades to the rotor. Blade "root" sections insert into slots machined into casings or rotors, or into discs mounted on the shaft (Figure 10-3-6) to stiffen the blades and, to obtain maximum efficiency, "shroud rings" are secured over the rotor blade tips (or blade tip extensions called "tenons"), which are then peened over or welded. Radial seal strips installed opposite the shroud bands and casing diaphragms further minimize steam leakage past the blades.

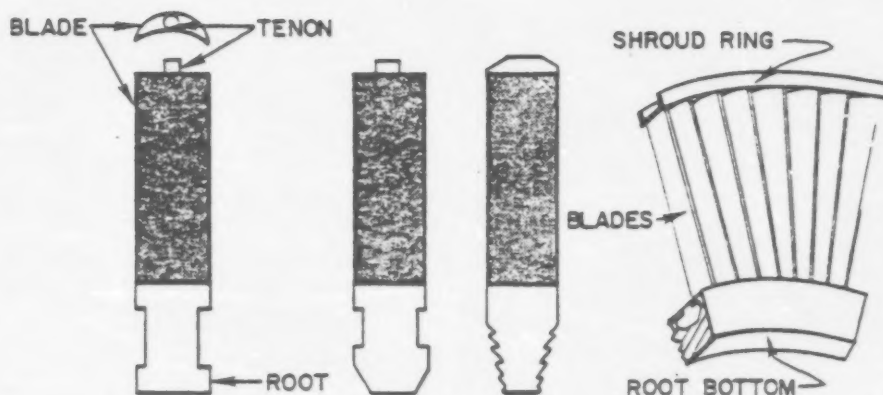


Figure 10-3-6. Turbine blade types and arrangement.

Nozzles and Diaphragms

Nozzles provided on impulse type turbines direct steam into the buckets mounted on the rotor discs. For present-day turbines, nozzles made of corrosion-resistant steel alloys are either of the convergent or convergent-divergent type depending upon the application.

Diaphragms installed between successive stages in impulse turbines contain the nozzles. Made in halves, and split along the centerline, they are held in place by matching recesses machined into the upper and lower casing halves.

Casings

Casings are generally made in halves - split horizontally along the axis of the rotor. High-pressure turbine casings are constructed of specially alloyed steel to withstand the high pressure and high temperatures of the steam. Lower-pressure turbine casings may be made of either cast iron or low-carbon steel. Casing joints and flange surfaces

are accurately machined and made up metal-to-metal without gaskets.

Seals

Shaft seals installed wherever the rotor extends through the casing prevent steam leakage from the casing and air leakage into the casing, depending on the application. The types of shaft seals used include 1) carbon rings, 2) water labyrinth and 3) steam labyrinth, with the steam labyrinth used most often in large compound turbines.

Bearings

Bearings of several different types (ball bearings, ring-oiled journal bearings, pressure-lubricated journal bearings) support the turbine shaft radially. All large turbines use the pressure-lubricated journal bearings of either the plain or self-aligning type. Bearing shells, made in halves of either steel, cast iron or bronze, contain grooves (machined inside the shell) to anchor the bearing metal. Large journal bearings employ drilled oil-supply passages in their lower halves and grooves in their upper halves.

Thrust bearings are specially designed to absorb the end thrust produced by steam pressure differential across the turbine blading, and to maintain the rotor in its proper axial position. (Ball or roller bearings may be used for thrust absorption in smaller turbines.) Larger turbines use either of two special types of thrust bearings: 1) tapered land bearings or 2) pivoted segmental shoe (Kingsbury) bearings.

Steam-Admission Valves

A variety of valves control steam flow to and through a turbine. All turbines use stop or throttle valves, followed by some sort of governing or control valves. Turbine stop and/or throttle valves provide steam admission to the turbine during normal operation, and shut off the supply of steam during emergency situations.

Turning (Jacking) Gear

The turning gear, a motor-driven device, consists of a combination of gears (meshing with a ring gear mounted on the turbine shaft) that turn the rotor at a very slow speed. The turning gear rotates the turbine shaft continuously during turbine startup, after shutdown, and - to prevent rotor bowing or warping - whenever large temperature changes occur. Also, it provides a means of jacking the rotor over in small increments for inspection of turbine parts or for maintenance.

TURBINE CONTROL SYSTEM

There are two general categories of turbine control (governing) systems:

Mechanical hydraulic.

Electro-hydraulic.

Although components of the two systems differ in design, each performs the same basic functions and exhibits similar operating characteristics.

Turbine speed control is probably the most important function of the control system. Turbine governors maintain constant speed with varying load, or control and limit speed for variable-speed turbines. Constant-speed governors (used with turbine generators and speed-limiting governors) appear on mechanical-drive turbines of feedwater pumps, large fans and other variable-speed equipment. The three common types of mechanical governors include:

- Direct-acting centrifugal.
- Centrifugal-actuated relay.
- Oil-actuated relay.

The "heart" of a centrifugal governor is its weights. As turbine shaft speed increases the weights tend to move outward due to centrifugal force. As turbine speed decreases, the weights move inward. On a direct-acting centrifugal governor (Figure 10-3-7), an output spindle connected to

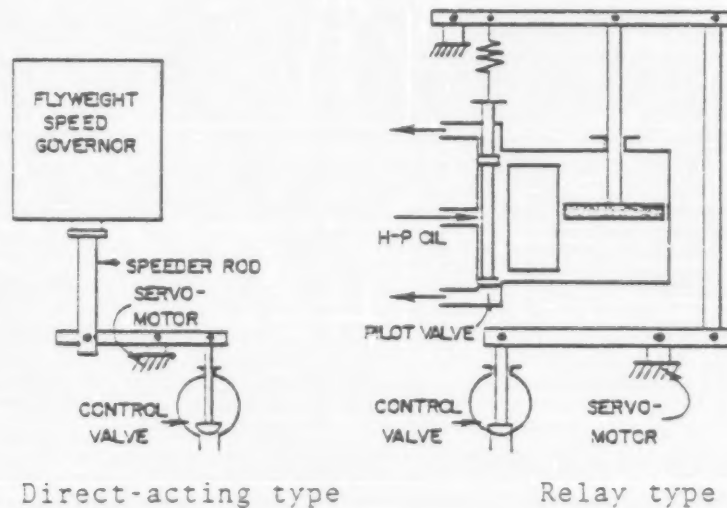


Figure 10-3-7. Centrifugal governor arrangements.

an actuating lever moves the control valve in the desired direction. On a centrifugal-actuated relay governor, the output spindle connects to a pilot valve that controls the flow of hydraulic fluid, under pressure, to the control valve hydraulic power piston (servomotor). The oil-actuated relay type differs from the centrifugal type only in that the pilot valve is actuated by the output of a centrifugal oil pump mounted on the turbine shaft.

TURBINE LUBRICATION AND HYDRAULIC SYSTEMS

Auxiliary turbine assemblies usually include a self-contained, force-fed oil system consisting of a shaft-mounted pump, an oil reservoir, an auxiliary oil pump, strainers, coolers and associated piping. This system provides all lubrication requirements, and it provides oil to the hydraulically-controlled governing system.

Such systems (Figure 10-3-8) must provide a low-pressure lubricating oil to all bearings, high-pressure oil to operate the hydraulic control mechanisms and, on large hydrogen-cooled generators, oil to seal the generator shaft against hydrogen leakage.

The main oil pump, usually a centrifugal pump, mounts on the turbine shaft toward the front. During normal operation, it provides all necessary lubricating and control oil. A motor-driven auxiliary oil pump, situated in the oil reservoir, provides oil to the system during turbine startup and shutdown (the shaft-driven main pump is adequate during normal operation). Also, a motor-driven pump, located in the oil reservoir, provides a supply of bearing oil whenever the turning gear is in use; however, this pump

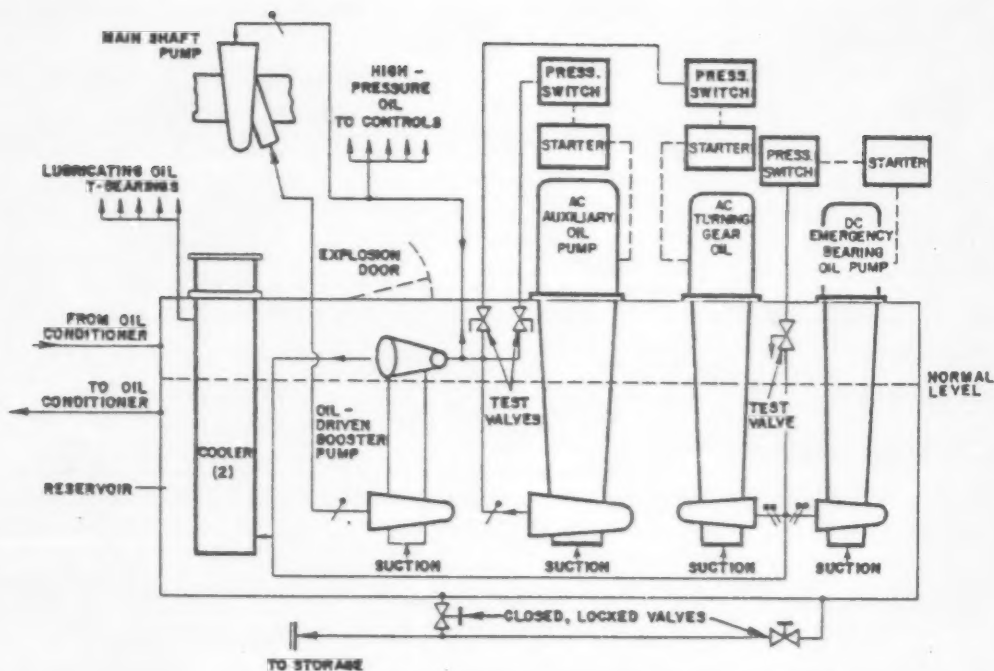


Figure 10-3-8. Hydraulic and lubricating oil systems.

is not designed to meet requirements of the hydraulic control system. An emergency bearing-oil pump, identical to the turning-gear oil pump, driven by a d.c. motor, backs up the bearing-oil system.

SHAFT SEALING STEAM SYSTEM

The sealing steam system provides high-quality steam to the shaft seals, preventing leakage of air into (or steam

out of) turbine cylinders at those points where the shaft extends through the casing. This system (Figure 10-3-9)

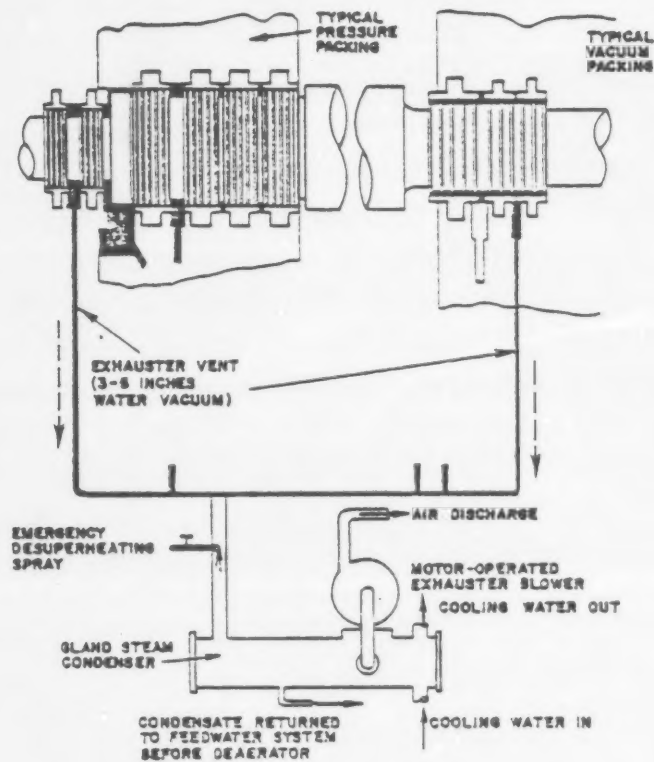


Figure 10-3-9. Typical steam-seal system.

consists of shaft packings, a seal steam regulator, a steam header, piping, an exhauster blower and a gland steam condenser.

TURBINE SUPERVISORY INSTRUMENTATION

Supervisory instruments, extremely important during startup, shutdown and large load changes, serve important functions during normal operation, also.

Shaft Eccentricity

The shaft eccentricity instrument detects and records the degree of shaft straightness.

Shaft Vibration

A vibration-measuring instrument detects the magnitude of vibration at various points along a shaft, usually at each main bearing. High vibration generally indicates abnormal or dangerous conditions within the turbine.

Shell Expansion

Shell (or casing) expansion detection instruments detect shell movement relative to a fixed (anchor) point on the turbine foundation.

Differential Expansion

The differential expansion detection instruments detect axial clearances between the turbine's rotating parts and stationary parts.

Rotor Position

A rotor position instrument detects axial position of a rotor thrust-bearing collar relative to thrust-bearing support, and indicates wear on thrust shoes.

Alarms

Alarms, associated with all supervisory instruments

(except the shell expansion detector and recorder) alert operators to abnormal or problem conditions.

TURBINE PROTECTIVE DEVICES

Protective devices back up the normal governing control devices to protect the turbine against mechanical and structural damage. Most turbines, regardless of size, have, as a minimum, some device to protect against dangerous overspeed conditions. Protective equipment on large steam turbines also protects against mechanical damage, thermal damage and overpressure as well as overspeed. Most protective devices connect, either hydraulically or electrically, to a common trip device that, when actuated, closes all steam admission valves.

Protective trips include:

- Overspeed.
- Low vacuum.
- High exhaust-hood temperature.
- Low bearing-oil pressure.
- Thrust bearing wear.
- Solenoid.

TURBINE OPERATION

Turbine system designs and installations vary so greatly that the inclusion of detailed operating instructions would be impractical. Turbine manufacturers usually provide such instructions for their individual units.

A controlled shutdown is just as important as a controlled startup. During period of load shedding (reduction)

and turbine shutdown, the control of turbine metal temperatures is of prime concern. Controlling the rate of temperature change minimizes thermal stress, differential expansion and vibration. During shutdown, when the predetermined minimum load has been reached, the turbine should be tripped immediately to abruptly shut off all steam flow through the turbine. The turning gear should be engaged immediately after rotor comes to a standstill.

Operation of a turbine under off-normal conditions, in most instances, should not be tolerated for any prolonged period of time. Under certain conditions, it is possible to tolerate an off-normal situation for short periods of time. But most off-normal conditions dictate a reduction in load if not an immediate trip. Some of the off-normal situations frequently encountered include:

- Off-frequency operation.

- Overloading.

- Water induction.

- Loss of load.

- Loss of sealing steam.

Off-frequency operation incurs the risk of turbine blade damage due to resonance vibration at certain under-frequencies.

Overloading the turbine (i.e., operating with higher-than-rated steam pressure and/or flow) in excess of design margins built into the unit can reduce its operational life and increase maintenance requirements.

Water induction into the turbine can cause severe damage to the blading, rotor, seals, casings and thrust bearings.

TURBINE MAINTENANCE

Proper and timely maintenance of a turbine ensures unit reliability and efficiency and minimizes unscheduled outages.

Preventive Maintenance

Preventive maintenance includes periodic inspection of turbine parts, lubricating system and control system checks, operational tests of protective devices and supervisory instruments, and running maintenance on turbine auxiliary systems. In addition, a good PM program includes accurate records of performed maintenance, calibration checks, operational tests, performance data and daily operational data.

Corrective Maintenance

Corrective maintenance includes repair of faulty equipment, modification of equipment or systems, and installation of new or additional equipment. Corrective maintenance is usually scheduled in a timely manner such as on a daily basis, weekend, next unscheduled outage or during a scheduled outage. A good maintenance and planning program is necessary to avoid delays and control costs.

A very thorough inspection and overhaul of a turbine should be scheduled after one full year of operation and at four- to five-year intervals thereafter. Turbines should be completely disassembled, except for the lower casing halves and foundation. Turbine inspection for potential maintenance needs includes:

- Bearing wear.

- Erosion of internal parts.

- Deposits or buildup on rotating and stationary blading and nozzles.

Structural damage, such as cracking or distortion of parts.

Wear on labyrinth seals and seal strips.

Wear on valve seats and bodies and control-system components.

This list identifies only a few of the many items to be examined (and repaired if necessary) during a complete inspection. After reassembly, certain preoperational tests and checks must be conducted to ensure that the turbine is ready for return to service.

GENERATORS

There are two basic types of electrical generators: direct current (d.c.) and alternating current (a.c.). The utility industry is primarily concerned with a.c. generating equipment; therefore, this module concentrates on a.c. generators (Figure 10-3-10).

GENERATOR DEFINITION AND CLASSIFICATION

The basic principle of electrical generation involves relative motion of a conductor in a magnetic field that causes a voltage to be induced into the conductor. Most d.c. generators and small a.c. generators use stationary field windings and rotating armatures. But, on larger generators, such as those found in power plants, the field (called a rotor) revolves and the armature (called a stator)

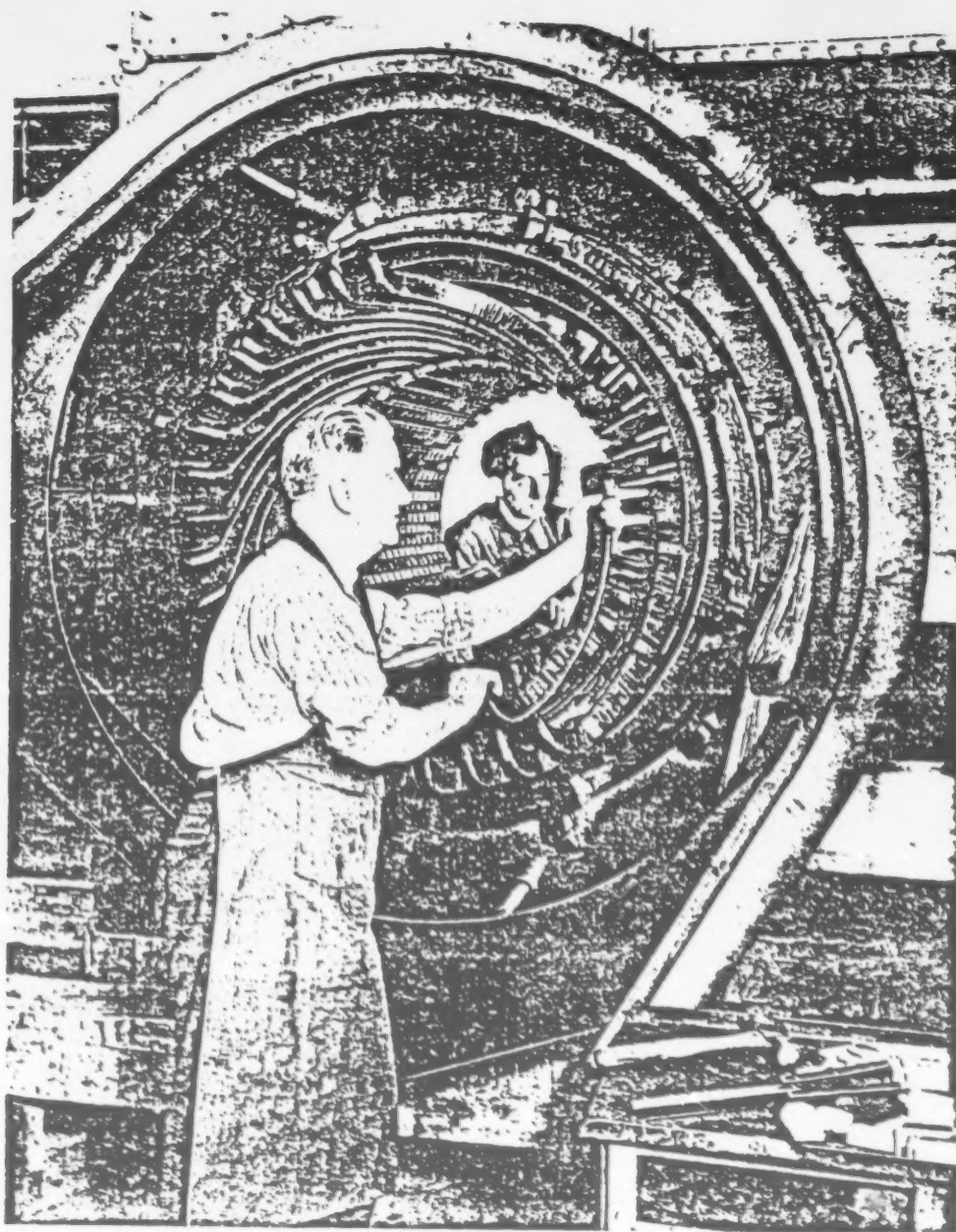


Figure 10-3-10. Coils being placed in slots of stationary armature of steam-turbine-driven a.c. generator. (General Electric Co.)

is stationary.

GENERATOR CONSTRUCTION

The rotating field generator lends itself to certain economic and structural advantages: the relatively low field current only needs to be conducted through the brushes and/or collector rings; it is much easier and less expensive to construct a rotating field than a rotating armature; also, because the power generated in the stator is usually much higher than that impressed on the field coils, stator coils must be insulated against these higher voltages and currents. Similar insulation on a rotating armature would be impractical.

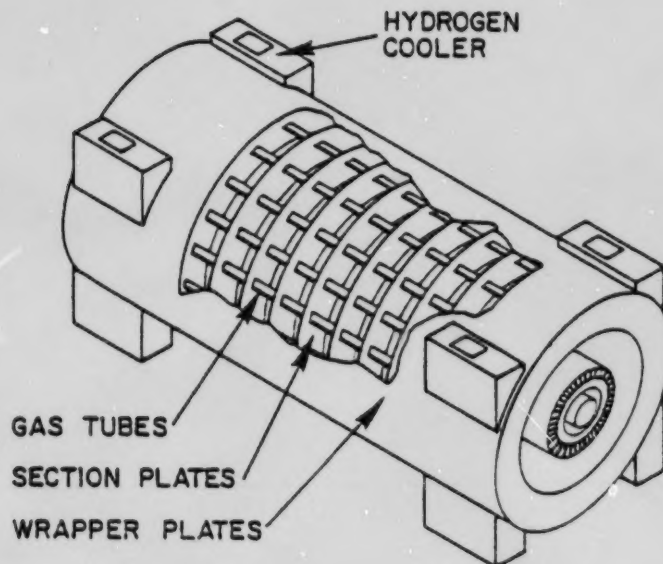
STATOR

The generator stator consists of a frame (or casing), a core assembly and windings.

The frame (Figure 10-3-11), fabricated from heavy steel plate with the interior sectionalized to provide ventilation zones for balanced cooling, supports the weight of all internal components, including the field. The stator frame contains the rotor bearings, shaft seals, hydrogen coolers, stator core and windings, and cooling gas and water manifolds (on certain types).

The stator core is cylindrical in shape, made of high-permeability (low magnetic resistance) steel, and fully encloses the circumference of the rotating field. The core provides a return path for the lines of magnetic flux created in the rotating field, and it supports the coils of

Figure 10-3-11.
Generator stator
frame.



the stator windings. The same rotating magnetic field that induces voltage in the stator windings also causes a voltage to exist in the stator core. This voltage causes a current to flow axially along the core in a closed loop, resulting in increased heating and higher field currents. Thus, to prevent current flow in the stator core, the core is laminated rather than being constructed in one solid piece.

The laminations are stacks of segmented sheets of steel inside the steel outer frame of the generator. Each lamination is insulated on both sides and has holes, slots and keyways punched out of the steel sheet. When stacked and clamped tightly together, they form a cylinder, keyed to the frame, with slots located on the inside diameter for the windings, and axial holes for cooling-gas flow-through. At certain intervals, a spacer piece placed between laminations provides a cooling-gas channel between the rotor

air gap and the frame.

The stator windings consist of insulated rectangular bars made up of copper strands and positioned into the stator core slots. Also, on water inner-cooled generators, a water header is attached to each end of the stator bars (Figure 10-3-12). Individual copper strands connect to

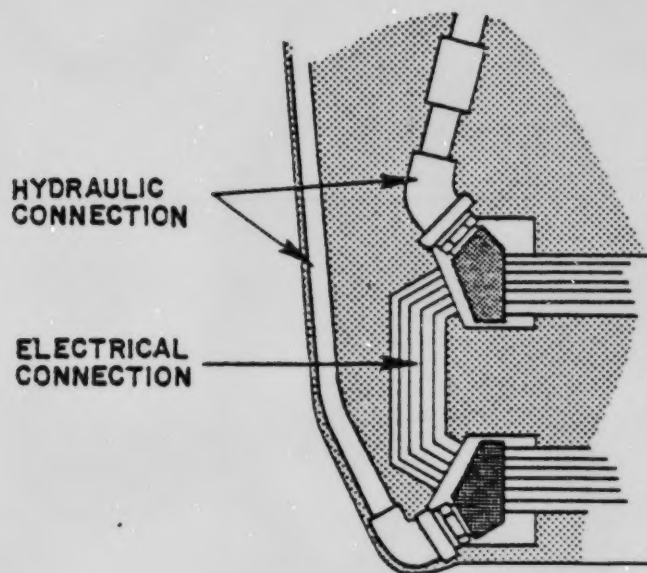


Figure 10-3-12.
Stator bar-end
connections.

the water headers. A laminated electrical shunt connection exists between the coil bars. Hoses are attached from the stator bar ends to the water inlet and outlet manifolds. At each end of the generator, stator bars connect to each other to form the coils.

ROTOR

The generator rotor contains a rotating magnetic field and consists of the following basic components:

- Rotor body.
- Field windings.
- Retaining rings.
- Collector rings.
- Field leads (mentioned above).
- Cooling fans.

GENERATOR AUXILIARY SYSTEMS

Auxiliary systems that provide support to the generator during normal as well as emergency operation include:

- Seal-oil system.
- Stator cooling system.
- Hydrogen cooling system.
- Air cooling system.
- Excitation system.

SEAL-OIL SYSTEM

The generator seal-oil system (Figure 10-3-13) provides high-quality oil, under pressure, to the shaft seals to prevent hydrogen gas leaks along the shaft where it extends through the generator casing. System components consist of pumps, coolers, regulating valves, filters, drain tanks and system piping.

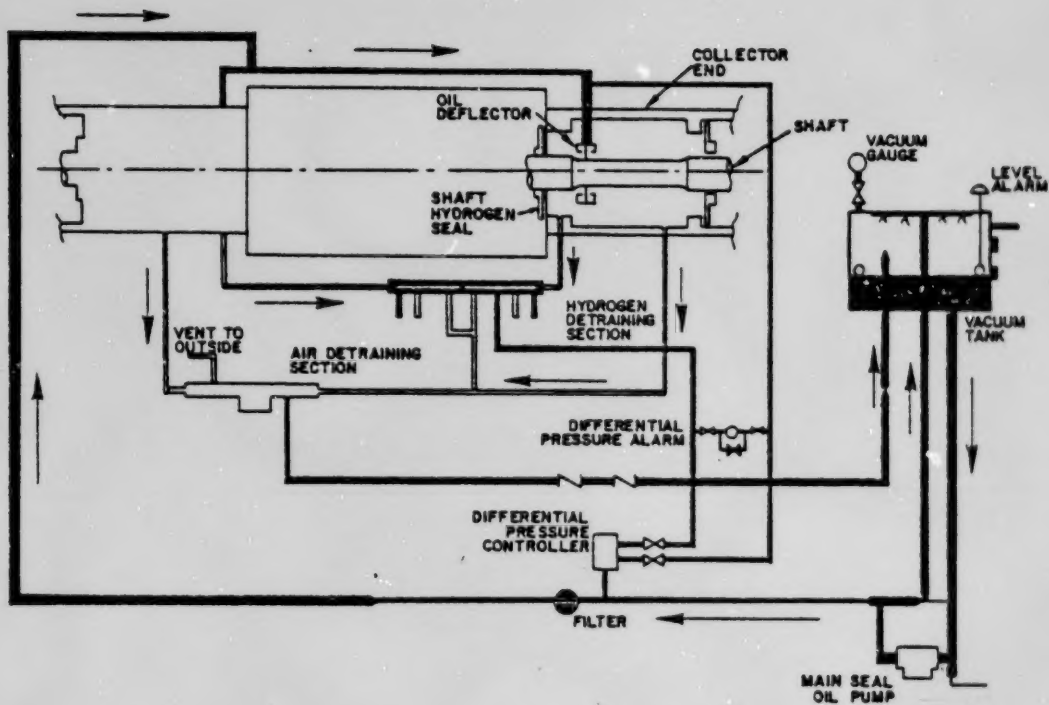


Figure 10-3-13. Vacuum-type generator shaft-sealing system for hydrogen-cooled generator.

STATOR COOLING SYSTEM

The stator cooling system circulates a coolant through the individual hollow strands of the stator coils (windings) to remove heat generated in the current-carrying conductors. The two coolants used on large generators for direct conductor cooling are high-pressure hydrogen gas and highly pure deionized water; however, the latter is most widely used because of its greater heat transfer capability and inertness to conduct or insulate.

HYDROGEN COOLING SYSTEM

The hydrogen cooling system provides a cooling medium for removing heat losses from the generator rotor (field) and stator core (armature). Hydrogen, selected as a coolant because of its desirable specific heat and density characteristics, provides low windage losses, excellent heat transfer, and is noncorrosive and will not support combustion.

Components of the hydrogen cooling system include a fan (installed on the generator shaft), coolers, pressure regulators, dryer, gas supply and distribution manifolds, system piping and controls.

AIR COOLING SYSTEM

Smaller generators are usually air cooled. That is, cool air is circulated around the rotor and through the stator windings. Usually totally enclosed, the cooling system consists of fans mounted on the generator shaft, air coolers and the necessary duct work.

EXCITATION SYSTEM

Excitation systems provide the power necessary to create a magnetic flux in the generator field windings. The two general categories of excitation systems include 1) the brush type and 2) the brushless type. Either type system provides very high reliability while performing adequately and economically.

Brush Excitation

This exciter generator (Figure 10-3-14) consists of

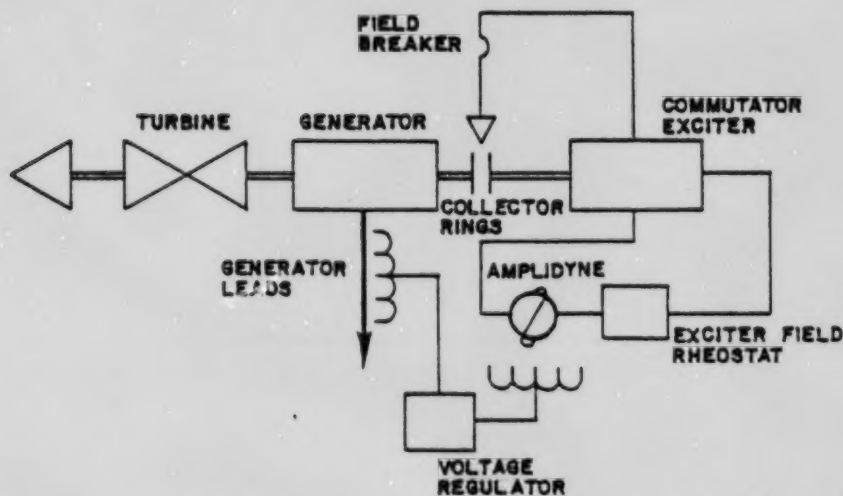


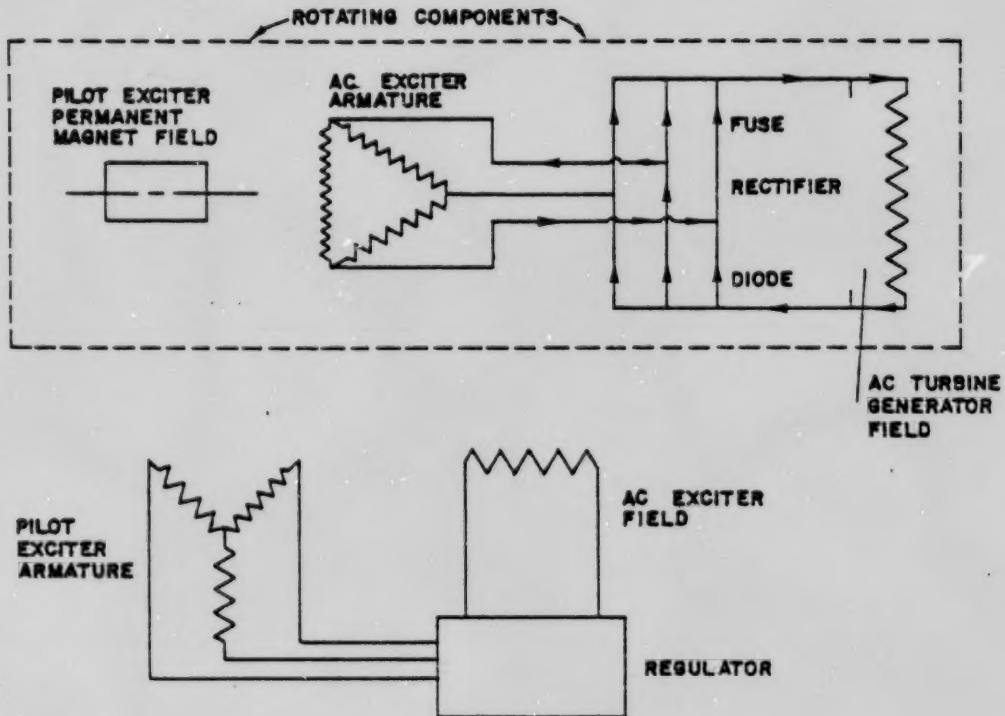
Figure 10-3-14. Brush-type commutator exciter system.

a stationary field and a rotating armature. The commutator and associated brushes convert the a.c. power generated in the armature to d.c. power required for the main generator field.

The exciter can be either shaft driven or motor driven. When the exciter is shaft driven, it is mounted to the main generator shaft. Thus, the turbine driving the main generator also provides motive force for the exciter, usually through a reduction gear, to maintain optimum commutator speed. This arrangement minimizes maintenance on the commutator and prolongs brush life.

Brushless Excitation

The brushless-type excitation system (Figure 10-3-15)



NOTE: ROTATING COMPONENTS ARE MOUNTED ON THE SAME SHAFT

Figure 10-3-15. Rotating rectifier excitation system.

deletes any need for a commutator and its associated brushes. One type of brushless excitation system utilizes an exciter generator coupled with a group of rectifiers. The rectifiers provide the direct current necessary for the main

generator field.

VOLTAGE CONTROL

A voltage regulator controls the excitation system automatically to maintain the generator terminal voltage at some selected value.

Rheostat

One of the simplest methods of controlling main generator output voltage is with a rheostat (Figure 10-3-16) placed in series with the exciter field.

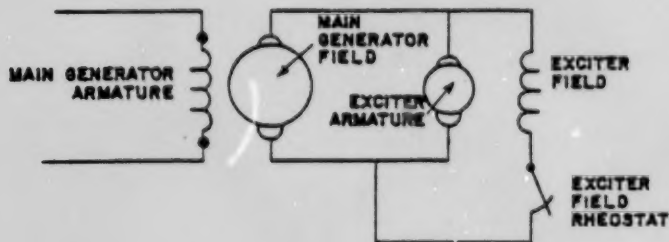


Figure 10-3-16.
Rheostat voltage-control system.

Amplidyne

In an amplidyne voltage-control system (Figure 10-3-17) a special 420-Hz, motor-driven, d.c. generator varies the exciter field strength.

Static Field

The static field voltage-control system (Figure 10-3-18)

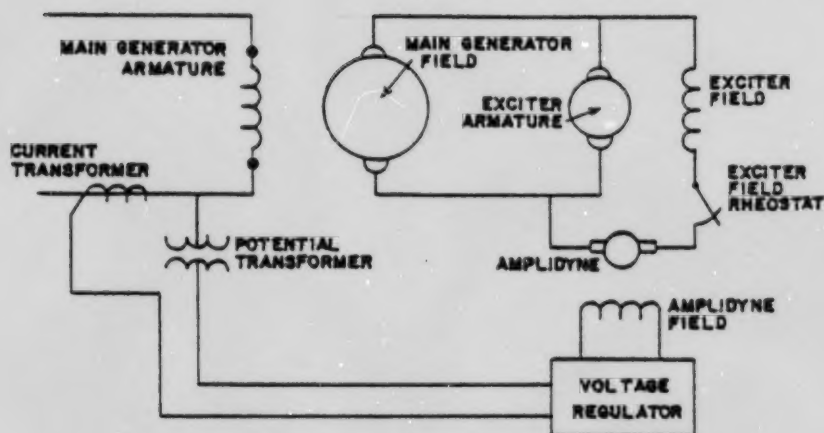


Figure 10-3-17. Amplidyne voltage-control system.

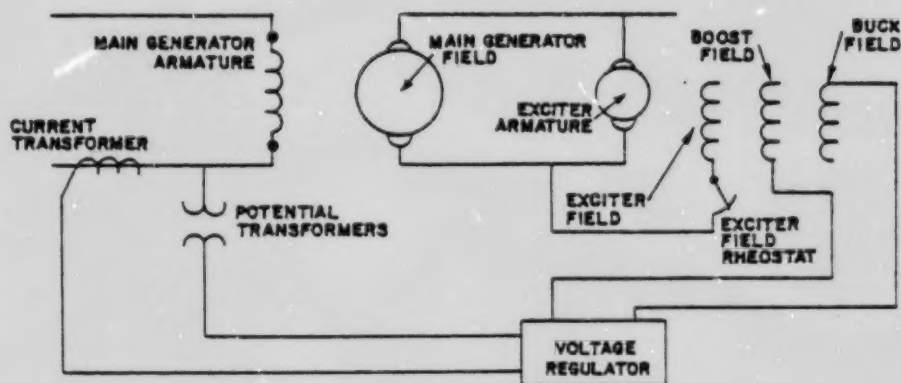


Figure 10-3-18. Static field voltage-control system.

utilizes a voltage regulator unit similar in operation to that used in the amplidyne system; however, instead of supplying power to an amplidyne field, the voltage regulator feeds two windings installed with the stator windings of the main exciter.

Pilot Exciter

In a brushless-type excitation system (Figure 10-3-19),

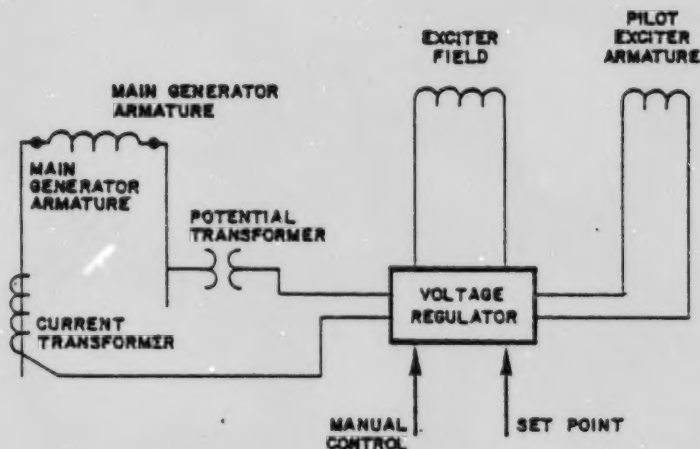


Figure 10-3-19. Brushless excitation voltage-control system.

self-excited generators cannot be used. Rather, a separate, permanent-magnet generator, called a pilot exciter, supplies the main exciter field.

GENERATOR INSTRUMENTATION

Instruments monitor and supervise the operation of large, modern generators. The more important parameters that must be indicated or recorded include:

Generator gross electrical output. Displayed, recorded and metered.

Generator net power output. Metered.
MVAR, in and out. Indicated and recorded.
Generator terminal voltage. Indicated and recorded.
Power system frequency. Indicated and recorded.
Rotor (field) temperature. Indicated and recorded.
Generator phase amps. Indicated.
Generator field amps. Indicated.
Generator field voltage. Indicated.
Hydrogen pressure. Indicated.
Hydrogen purity. Indicated.
Stator winding temperatures. Recorded.
Stator cooling water temperatures and conductivity.
Recorded.

In addition, annunciators are installed to indicate any electrical system alarms.

GENERATOR PROTECTIVE DEVICES

Generators can experience various types of internal faults in either the stator or the rotor; more common faults include:

- Phase-to-phase.
- Phase-to-ground short circuits.
- Overcurrent.
- Loss of field.
- Underfrequency.

High-speed relays protect the generator from damage caused by internal faults, some of which are listed above.

DIFFERENTIAL RELAYS

Differential relays protect the generator from damage caused by a 3-phase fault, a phase-to-phase fault or a phase-to-ground fault.

GROUND RELAYS

Ground relays protect the generator from damage caused by a ground fault occurring in any of the windings.

LOSS-OF-FIELD RELAYS

Loss-of-field relays protect the generator from thermal damage due to decrease or loss of excitation. They also protect or minimize instability effects on power system due to voltage decrease caused by low excitation.

UNDERFREQUENCY PROTECTIVE RELAYS

Underfrequency protection relays protect the turbine from possible damage to turbine blading due to blade resonance.

NEGATIVE-SEQUENCE OVERCURRENT RELAYS

Negative-sequence overcurrent relays protect the generator against thermal damage caused by external (power system) unbalanced faults.

GENERATOR OVERVOLTAGE RELAYS

A generator overvoltage relay affords protection against overexcitation of the generator and connected transformers.

GENERATOR OPERATION

Generator design, size and auxiliary systems vary to such a large degree that to include detailed operating instructions for the various types would be impractical. The generator manufacturer usually provides detailed operating instructions for the individual units. This, the following instructions are generalized for a "typical" large, modern generator.

Normal operation of the large hydrogen-cooled and liquid-cooled generators involves significant and various operating temperatures. Therefore, generator loading is accomplished strictly in accordance with a "capability curve" associated with that particular generator.

This capability curve is used to limit hotspot temperatures in the stator and rotor windings, and in the stator core. It shows "kilowatt" loading versus "kilovar" loading. Also, it gives the limits of generator loading at various hydrogen gas pressures. Lines of constant power factors are also included on the curve.

STARTUP

Recommended procedures may vary from one manufacturer

to another. The following steps suggest a general procedural sequence:

Place in service all auxiliary systems: seal oil, hydrogen cooling, stator cooling, lube oil.
Bring generator up to speed in accordance with turbine startup recommendations.

As generator approaches rated speed close the field breaker to apply field excitation (due to residual magnetism), though not enough for rated voltage.

Increase machine terminal to rated voltage by reducing resistance in exciter field circuit.

After manually increasing voltage, place automatic voltage regulator in service; set voltage adjustor to maintain desired voltage.

Bring generator into synchronism with power system; close main generator breaker.

After generator is synchronized, determine rate of loading by placing restrictions on the turbine (higher temperature and greater stresses and strain may be imposed on many turbine parts than are tolerable on generator components).

SHUTDOWN

Reduce load at a rate consistent with restrictions placed on turbine.

When generator load approaches zero, open generator main breaker.

Remove voltage regulator from service.

Insert full field resistance and open generator field breakers. (Good operating practice calls for removal of excitation prior to unit reaching 25% of rated

speed - if not done, field temperature could exceed design due to lack of proper ventilation).

Note: Usually the generator auxiliary systems remain in service during the shutdown period.

ABNORMAL CONDITION OPERATION

Power plant generation design anticipates a 40-year service life; however, this life expectancy may be shortened by operation under any of the abnormal conditions listed below:

- Overloading.
- Abnormal voltage.
- Off-frequency.
- Excitation loss.
- Motoring (or motorizing).

GENERATOR MAINTENANCE

An effective generator maintenance program minimizes unscheduled outages for equipment repair and replacement. Thus a regular maintenance and inspection program is a must.

Adjustment and replacement of collector ring brushes and exciter commutator brushes must be accomplished periodically, as well as repairs of any hydrogen and oil leaks, along with regular cleaning of coolers and filters and the running maintenance repair of auxiliary system components.

Major maintenance inspections involving complete remov-

al of the rotor also should be conducted periodically, usually at the same frequency as the turbine disassembly.

(Note: On hydrogen-cooled generators, prior to opening for inspection, hydrogen gas must be purged from the casing.)

The electrical parts of the stator, inspected and repaired as necessary, include:

- Stator windings.
- Coil bracing and wedges.
- Stator core laminations.
- Phase terminal bushings.

Rotor inspection includes slot wedges, collector rings and leads, and end windings.

Mechanical parts, inspected and repaired as necessary, include:

- Couplings.
- Gland seals.
- Bearings.
- Bearing insulation.

Auxiliary systems equipment should be inspected and repaired as necessary.

A good maintenance program also includes testing of certain generator components. These tests normally include:

- Conductor insulation.
- Overpotential.
- Ground insulation.
- Rotor.
- Stator windings.
- Exciter windings.
- Temperature detectors.



EXERCISES

From the text, answer the following questions.

1. Any power plant revolves around its _____ -
_____ combination - all else is auxiliary to this tandem system.
2. List the three major auxiliary systems associated directly with the power generating turbine.
3. List six types of instrumentation associated with the turbine.
4. List the six types of hazards that trip the turbine.
5. Name the two types of maintenance associated with turbines and generators.
6. Name the two basic types of electrical generators.
7. What are the two major components of a generator?
8. There are five major generator auxiliary systems; name them.
9. What is a "fault?" Name five common faults experienced by generators.
10. Power plant generator design anticipates a _____ -
year service life.



MATERIALS

Small steam turbine (available at small cost from any supplier).

Assortment of turbine bearings and seals.

Shaft eccentricity detector.

Shaft vibration measuring instrument.

Generator (a.c.).

Brush set (spare).



PROCEDURES

1. Operate a small steam turbine of the simplest design; on Data Table 10-3-1 list ways efficiency can be improved; try each and record results.
2. Identify (on Data Table 10-3-2) various kinds of bearings and seals, either from examples or illustrations provided by instructor; indicate purpose of each.
3. Measure shaft eccentricity and vibration of simple turbine device (use appropriate measuring equipment); record results on Data Table 10-3-3.
4. Disassemble an a.c. generator; identify components and parts (on Data Table 10-3-4); reassemble.
5. Change brushes in a generator or motor.
6. Take field trip to power generation plant; record information called for on Data Table 10-3-5.



DATA TABLE

DATA TABLE 10-3-1

Efficiency Improvement Procedures	Improvement	No Improvement
1.		
2.		
3.		
4.		
5.		
6.		

DATA TABLE 10-3-2

Item	Seal	Bearing	Description of Nomenclature
1.			
2.			
3.			
4.			
5.			
6.			
7.			
8.			

DATA TABLE 10-3-3

Shaft Speed	Vibration	Eccentricity
rpm		
rpm		
rpm		

DATA TABLE 10-3-4

Component	Parts
1.	
2.	
3.	

DATA TABLE 10-3-5

Item	
1. Generator Gross Electrical Output	_____.
2. Generator Net Power Output	_____.
3. MVAR	in _____ out _____.
4. Generator Terminal Voltage	_____.
5. Power System Frequency	_____.
6. Rotor (field) Temperature	_____.
7. Generator Phase Amps _____, Field Amps _____.	
8. Generator Field Voltage	_____.
9. Hydrogen Pressure _____, Hydrogen Purity _____.	
10. Stator Winder Temperatures _____, _____,	_____.
11. Stator Cooling Water Temperatures _____,	_____.
12. Stator Cooling Water Conductivity	_____.



REFERENCE MATERIALS

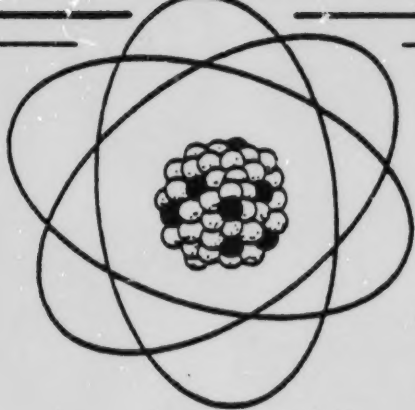
Babcock and Wilcox Co. Steam: Its Generation and Use.
 New York: B & W, 1975.



2. Describe the major mechanical components, control systems, auxiliary systems and protection and safety devices and systems of a typical steam turbine:
3. Identify the various types of supervisory instruments necessary for turbine control:

4. Discuss turbine operating procedures and prescribe general turbine maintenance requirements:
5. Define and classify the basic types of generators used to generate electricity in a nuclear power plant:
6. Describe the major mechanical components of a typical generator:

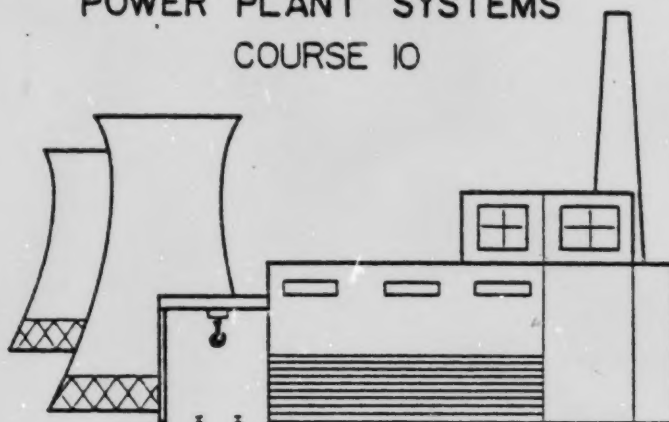
- 121



NUCLEAR TECHNOLOGY

MODULE 10-4 HEAT EXCHANGERS AND CONDENSERS. -
GERALD C. WALLACE

POWER PLANT SYSTEMS
COURSE 10



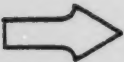
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COURSE MODULES

COURSE 10 POWER PLANT SYSTEMS

- 
- MODULE 10-1 Power Plant Fundamentals
 - MODULE 10-2 Power Plant Thermal Cycles
 - MODULE 10-3 Turbines and Generators
 - MODULE 10-4 Heat Exchangers and Condensers
 - MODULE 10-5 Pumps
 - MODULE 10-6 Valves and Piping
 - MODULE 10-7 Electrical Transmission and Distribution Systems
 - MODULE 10-8 Power Plant Fundamentals (Fossil-Fuel Energy Efficiency)
 - MODULE 10-9 Fossil Plant: Auxiliary Discussions

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Technical Education Research Center
Southwest
4201 Lake Shore Drive, Suite 111
Waco, Texas 76710



INTRODUCTION

The overall cycle of a nuclear-fueled power plant incorporates many heat exchangers. The purpose of each is to transfer heat from one fluid to another. Even a condenser is a type of heat exchanger - one fluid (vapor) is translated into another (liquid). The main idea, in a nuclear-fueled power plant, is to take the heat generated within the fuel pellets and use the energy of this heat to (ultimately) generate electricity.

But the energy of heat, as it is liberated from the reactor core, is not in a suitable form for generating electricity; it must be converted, initially into high-pressure steam. This conversion is accomplished (in a PWR) by means of a cycle of heat exchangers.

This module acquaints the student with uses and operations of heat exchangers in various applications throughout the plant.



MODULE PREREQUISITES

The student should have completed Course 4, "Heat Transfer and Fluid Flow," and Module 10-1 of this Course.



OBJECTIVES

Upon completion of this module, the student should be able to describe basic function of each of the following heat exchangers (normally found in a nuclear-fueled power plant):

- Shell-and-tube heat exchanger.

- U-tube steam generator.

- Once-through steam generator.

- Main condenser.

- Feedwater heater.

- Cooling tower.

- Spray pond.



HEAT TRANSFER

One of the more basic formulas dealing with heat transfer may be written as follows:

$$Q = VA \Delta t.$$

Equation 10-4-1
(Equation = Eq.)

where

Q = heat transfer rate, Btu/hr.

V = overall heat transfer coefficient, Btu/hr-ft²-°F.

A = heat transfer area, ft².

Δt = temperature difference, °F.

This equation, presented in Course 4, is further discussed here. Note that the greater the temperature difference the higher the rate of heat transfer. Heat is a basic form of energy and its driving force is temperature difference.

A basic law of physics notes that heat energy always flows from the highest temperature to the lowest temperature; thus, the greater the difference in temperature, the greater the transfer of energy. If a larger surface area is available for heat transfer, increased heat transfer is obvious.

Not quite as obvious, however, is the difference in heat-transfer coefficient. This variable depends upon the materials through which the heat is being transferred.

Steel and most metals transfer heat quite readily and have high coefficients; materials such as glass and fiberglass are good insulators and have very low coefficients.

DESIGN

Designers evaluate each of these criteria when developing an appropriate (efficient) heat exchanger for a particular application; many tradeoffs may be made in an attempt to get the most heat exchanger for the money. The Δt is established by the system; thus, selection focuses primarily on surface area and heat-transfer coefficient.

Size should be kept as small as possible because larger exchangers 1) require more material for construction, 2) require larger buildings or rooms to allow for operation or maintenance, and 3) lose more heat to the environment, thereby reducing efficiency of the system and increasing ventilation requirements. All of these aspects increase costs. And costs must be considered. For example, silver has one of the best coefficients but is too expensive for most heat exchanger applications.

Chemical characteristics also affect materials selection; a material is of little value, regardless of its heat-transfer characteristics, if it has to be replaced frequently.

Strength is important: material thickness must be kept to a minimum to minimize energy losses. Stainless steel is used frequently because it performs well (except when the medium is salt water, which attacks stainless steel quite readily). Copper-based alloys, such as Monel and Admiralty,

perform well in a saltwater environment.

In a nuclear-fueled power plant, the water carries radioactive contaminants; therefore, extra expense is warranted to ensure that system integrity is not violated. Exotic metals such as titanium may be used (silver, by comparison, is cheap).

HEAT EXCHANGERS

The simplest heat exchanger is a container in which two different-temperature fluids are mixed. The two obtain the same temperature as heat is transferred from the hotter fluid to the cooler one. A few simple applications such as this are found in power plants; for example:

Open feedwater heaters.

Desuperheaters.

Jet condensers.

Most heat exchangers, however, have the two fluids separated by a wall through which heat is transferred. The simplest of these is a tube within a tube, with the fluids separated by the wall of the inner tube. This heat exchanger is a "counterflow" type - one fluid flows in one direction and the other fluid flows in the opposite direction (Figure 10-4-1). The heat of the hotter fluid transfers to the cooler one in accordance with the formula studied earlier. This arrangement limits the area of transfer, thus it finds limited application.

The most common type of heat exchanger is the shell-

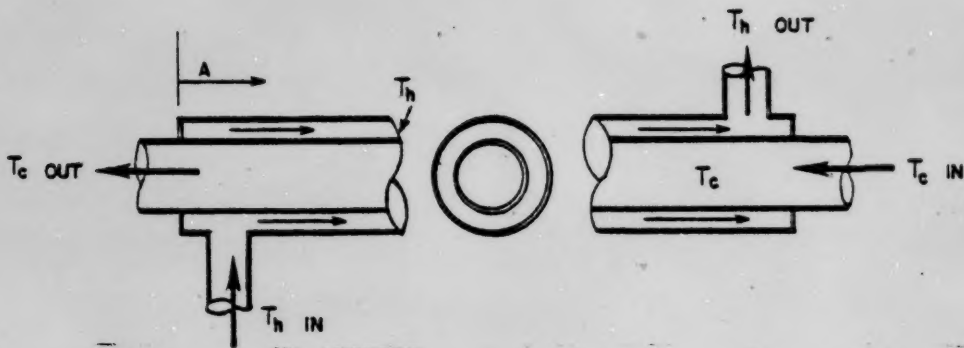


Figure 10-4-1. Tube-within-a-tube counterflow heat exchanger.

and-tube (Figure 10-4-2). An outer casing (shell) contains a large number of tubes through which one of the fluids passes. The other fluid is contained only by the shell and flows freely around the tubes. The shell side (shaded in Figure 10-4-2)

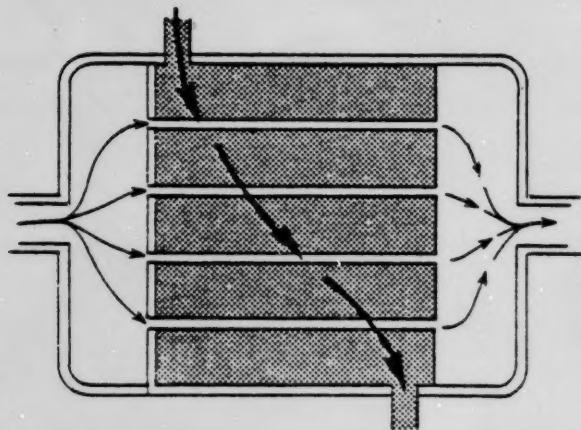


Figure 10-4-2. Shell-and-tube heat exchanger.

is normally only one pass across the tubes, from one end of the shell to the other, or from the center to the ends. But, with baffles, it can make many passes across the tubes (Figure 10-4-3). Such baffles normally are used to direct

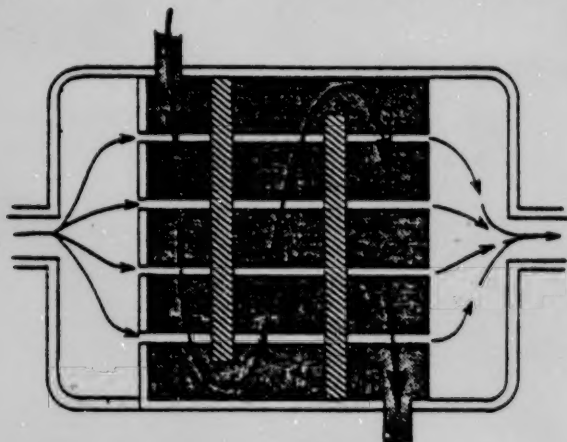


Figure 10-4-3. Shell-and-tube heat exchanger with baffles.

flow across the tubes, rather than along them. This turbulence improves heat transfer by breaking up stagnant films and increasing area of the stream in contact with the tubes.

The tube bundle may make one, two or even more passes either by making U-tubes (Figure 10-4-4) or by using baffles at the ends of the heat exchangers to direct flow from one bundle of tubes to another.

Most heat exchangers are counterflow, but some have parallel flow applications. (Counterflow means the two fluids flow in reverse directions within the heat exchanger.) Counterflow exchangers have two advantages: 1) the final temperature of the cooler fluid may exceed the outlet temperature of the hotter fluid (in parallel flow the temperature of the hotter fluid is always greater than that of the

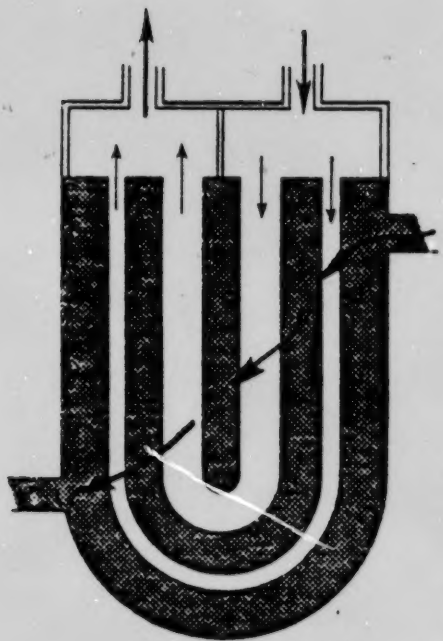


Figure 10-4-4
U-Tube heat exchanger.

colder fluid - so the two temperatures approach each other but never overlap) and 2) Δt is uniform along the full length of the tubes, making it more efficient and requiring less total surface area.

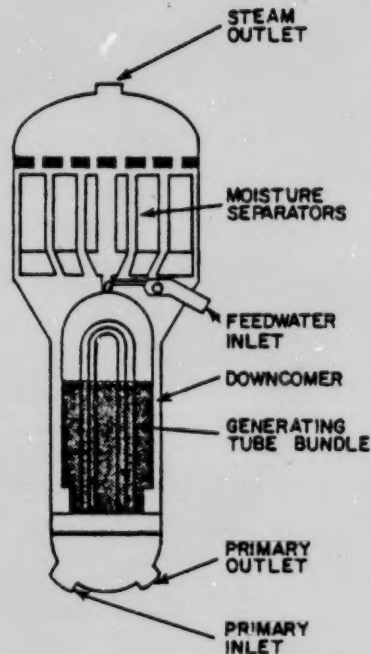
STEAM GENERATORS

Steam generators are specialized heat exchangers utilized in PWR's to generate the necessary steam for turbine operation. Steam generators are of two basic designs. Two major manufacturers, Westinghouse and Combustion Engineering, make U-tube steam generators; Babcock and Wilcox makes a straight-tube, once-through steam generator.

U-TUBE STEAM GENERATOR

The more common U-tube type (Figure 10-4-5) is discussed

Figure 10-4-5.
U-Tube steam generator
(only three tubes shown
for simplicity).



first. Hot water (from the reactor) enters bottom of steam generator; then it rises through the tubes and comes back down into other side of bottom. Inlet and outlet water are separated by a baffle plate. Feedwater is admitted to bottom of tube bundle and flows upward, picking up heat as it remains in contact with tubes and, eventually boiling to form steam. (Note that half of the length of each tube is counter flow and half is parallel flow (also, water in the tubes is going to become cooler on one side of generator)).

This type of generator produces "saturated" steam; that is, it contains moisture, which could cause severe equip-

ment erosion and impingement problems if not removed. (Moisture is removed by mechanical separators in upper part of steam generator.) Because of a difference in momentum of the steam and water, the heavier water is thrown out by centrifugal force as the steam spins upwards through the "cyclone" separators. Moisture is also removed as the steam is forced to abruptly change directions a number of times; the heavier water droplets contact the separator walls, then drain back into the steam generator. The result is "dry" steam (i.e., without moisture).

ONCE-THROUGH STEAM GENERATOR

The "once-through steam generator" (Figure 10-4-6) has

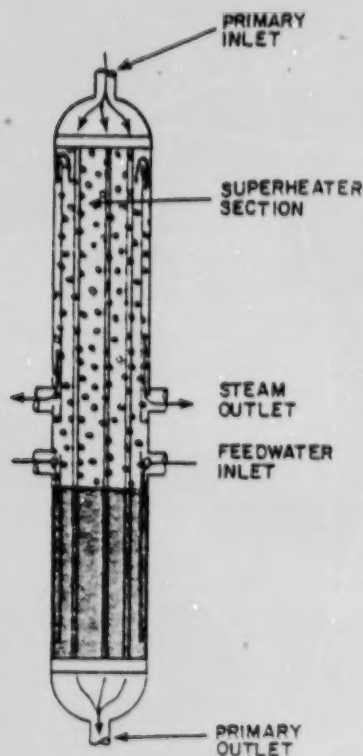


Figure 10-4-6.
Once-through steam
generator (only
three tubes shown
for simplicity).

reactor coolant entering at the top, passing down through the tubes and exiting at the bottom. This design provides some advantages but also imposes some restrictions. For example, extra care is necessary because tubes are rigidly attached at each end and could be buckled or stretched if excessive temperature differences are allowed to exist between reactor coolant (which determines tube temperature) and steam-generator shell temperature. During heatup, the shell is heated by a recirculation system with the system completely full, or by drawing a vacuum on the steam generator to form a steam cloud to heat the metal until temperature is high enough to build up a positive steam pressure. Steam, after leaving tube bundle at top, passes downward, between shell and an internal baffle, and exits near the bottom. This flow path helps to keep shell and tube temperatures close and helps hold thermal stresses within reasonable limits. Feedwater must also be heated to minimize stresses.

An important feature of this design is that it provides superheated steam at a constant outlet pressure, which increases overall plant efficiency.

CONDENSERS

A significant part of any power plant is a specialized heat exchanger known as the "main condenser." This condenser's primary function is to receive exhaust steam from the turbine and condense it back into water so that it can be returned to the steam generator and complete the closed

loop. Other functions include:

- Maintaining turbine exhaust pressure at a very high vacuum.

- Condensing bypass steam when turbine is off-line.

- Accommodating large volumes of heater drains when heaters are out of service.

- Helping to de-aerate condensate.

- Providing net positive suction head (NPSH) for condensate pumps.

It is too expensive to generate steam, allow it to pass through the turbine, and then just let it exhaust to the atmosphere. Modern plants have steam flows on the order of 15 million pounds per hour; that's too much to throw away. Getting low-pressure steam back into a high-pressure steam system is difficult, but the condenser removes sufficient heat from the steam to change it back to the liquid state so that it can be easily pumped into the steam generator.

Normally, cooling is provided by a huge bank (or banks) of tubes through which cool water is pumped. In this respect, the condenser is just a tube-and-shell heat exchanger, with steam contacting the cool tubes and condensing.

The same considerations are taken into account as in smaller tube-type heat exchangers. Heat load is established by plant size; cooling water temperature is fairly well established within reasonable limits by plant location; cooling water source determines which chemical properties are to be major considerations in tube material selection.

By looking at the familiar formula, $Q = VA\Delta t$, the only unknown is area, A . Plant size determines Q , cooling water temperature essentially determines Δt , and tube material (with appropriate fouling factors from water environment) determines V . Surface area, then, provides the key, as

always, to the number, length and diameter of tubes. Some installations alter the tubes to increase surface area by adding fins, ridges, flutes, and so on. But these appendages are not used (normally) in large condensers.

A property of steam of interest here is that energy release per unit of pressure varies greatly (over the pressure range found in a steam plant); that is, allowing pressure to change (by working through a turbine) from 10 psig to 5 psig will extract a given number of Btu's/lbm but, with 1000 psig steam, the pressure may have to drop 100 psig or more to get the same number of Btu's. This property continues below gage pressure, in the vacuum range, where it is more pronounced. To take advantage of this property, condensers are run at very high vacuums (26 to 30 inches of mercury), which greatly increases overall plant efficiency.

Any air that gets into the system (it can easily happen with the system under a vacuum) represents a possible corrosion problem; it ultimately could damage some of the tubes of the steam generator - one of the most serious accidents that can happen in a reactor plant. Condenser design helps to remove air from the water (gases naturally come out of solution as the water splashes down the tubes and baffles under the vacuum that exists).

Air that comes out of solution cannot be allowed to stay in the condenser (it would cover some of the tubes and reduce efficiency, or even build up a pressure in the condenser). Vacuum pumps pull a suction on the upper portion of the condenser to sweep the gases out. Steam flow paths also are directed to sweep the gases to the air removal section. Frequently, tubes in this area are of a different material to inhibit corrosion caused by gases concentrated there.

One consideration brought about by the vacuum maintained in the condenser relates to condensate pump performance. Water coming out of the condenser is very close to saturation temperature, thus it could easily flash to steam in the eye of the condensate pump. The lower volume of the condenser is called a hotwell and contains several feet of condensate, which supplies sufficient head to make up for any pressure loss in the pump suction and prevent such flashing.

FEEDWATER HEATERS

Feedwater heaters are primarily shell-and-tube heat exchangers. Many system features are used to squeeze every available Btu into the feedwater before it gets into the steam generator. Ideally, feedwater is at saturation temperature as it enters the steam generator; energy extracted from the primary cooling system can be used to convert that water to steam. But, plants cannot accomplish this ideal, though feedwater heaters do add measurably to overall efficiency.

Feedwater comes into the heater (Figure 10-4-7) and makes a pass through the U-tubes. The primary source of heat, extraction steam, enters top of heater and swirls over the tubes, heating feedwater. (Extraction steam comes out of the turbine after it has passed through some stages of the turbine blading.) The steam condenses (as it gives up its heat to the feedwater), drips over the lower tubes and collects in the bottom of the heater (providing another

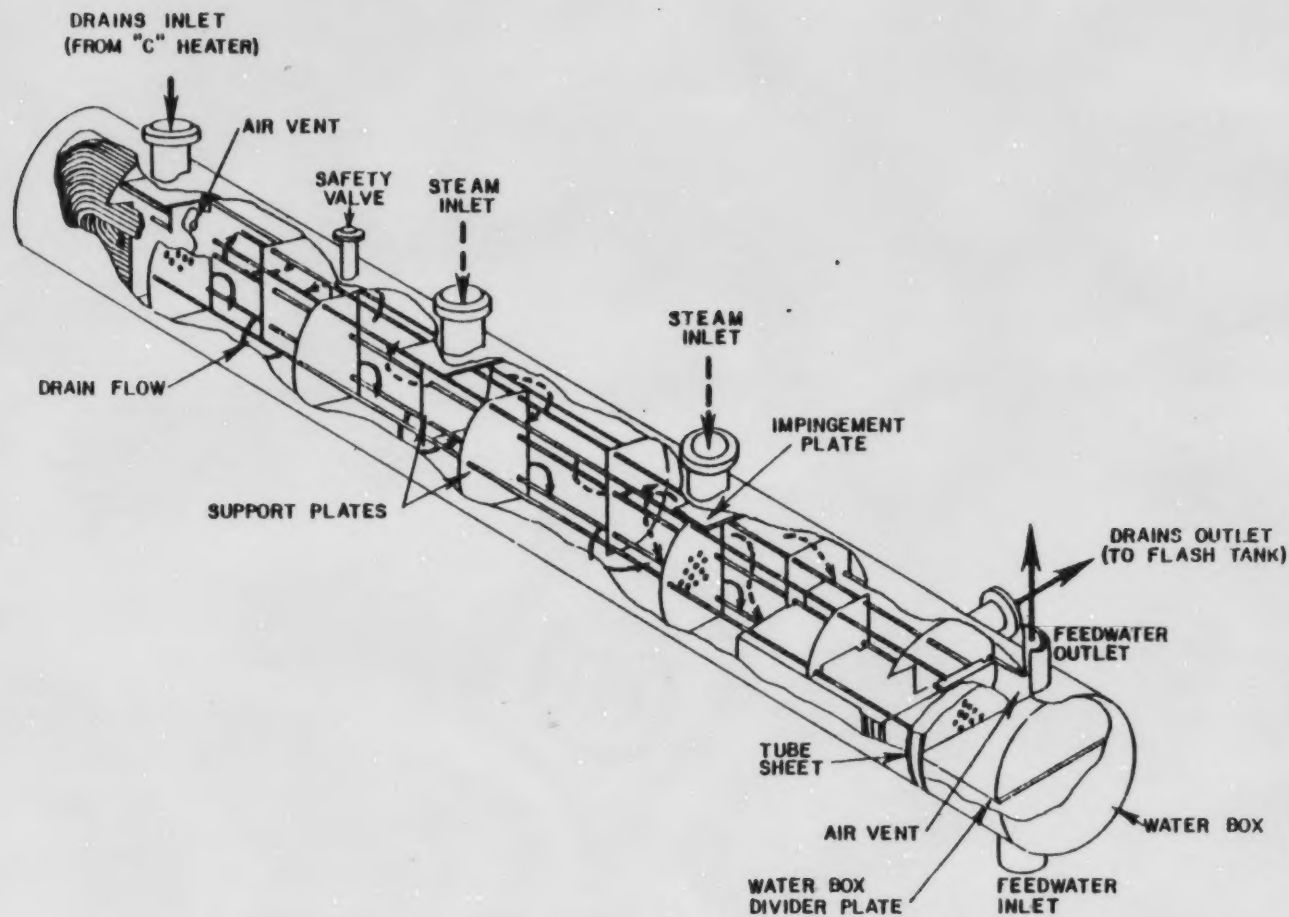


Figure 10-4-7. Feedwater heater.

source of heat that can be used, and is).

In summary, feedwater heaters consist of a feedwater stream, heating steam, drains from higher-pressure heaters to lower-pressure heaters, vents and, possibly, nitrogen purge lines.

COOLING TOWERS

A cooling tower provides cooling by breaking up water into small droplets to give it maximum surface area for cooling, which promotes airflow through the droplets, allowing the water to cool. Normally, water cooled in a cooling tower is the same circulating water that cools the main condenser.

There are two basic types of cooling towers:

Natural draft.

Mechanical draft.

Natural-draft towers are huge concrete structures, which dominate the plant site. The main structure is a large (300 feet across, 400 to 500 feet tall) hyperbolic chimney (Figure 10-4-8). Most towers of this design are empty and this high structure is nothing more than a chimney. Water gives up heat to the air, which makes it tend to rise, and the chimney is designed to promote this air flow, using the natural convection of the heated air.

Mechanical-draft cooling towers use large fans mounted in towers (Figure 10-4-9) to move air. With no necessity for promoting draft, these towers are much smaller, with one or more smaller chimneys located atop the lower

Figure 10-4-8.
Natural-draft
cooling tower.

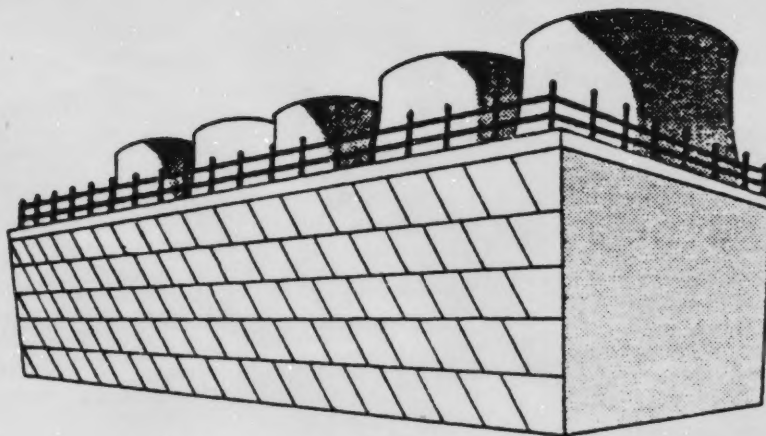


Figure 10-4-9. Mechanical-draft cooling tower.

Fans inside these smaller chimneys provide motive force for the air, which cools the water droplets.

The basic determination of which tower configuration to use is economy. Clearly, it takes more money initially to erect a large, concrete, natural-draft, cooling tower than it does to put up a more compact, mechanical-draft tower; however, long-term operating expenses of the two must be considered. Electrical power, to operate the fans and the extra maintenance requirements of the mechanical-draft system quickly offset the initial cost savings. It should be noted that some climatic conditions (e.g., the desert) tend to reduce effectiveness of a natural-draft configuration; thus, a mechanical-draft system may get the nod.

SPRAY PONDS

When a plant is constructed in an area in which space and water are no problem, spray ponds can be used as cooling reservoirs. Water is sprayed out of many nozzles situated about ten feet above pond water level. The spray droplets are cooled by direct contact with the air as they fall to the pond surface. The water is further cooled by losses to ambient as the water gradually moves through the pond to the intake point of the cooling water pumps.

For safety considerations this system has appeal because of its simplicity; all it requires is that a pump or two continues running, because all other components are static.



EXERCISES

None.



MATERIALS

5 small heat exchangers (different designs and different materials).

Detailed drawing(s) of a main condenser.

2 appropriate temperature-measuring devices.

Graph paper.



PROCEDURES

1. Use at least five small (less than six feet long) heat exchangers (provided by instructor); disassemble each and obtain the following information:

Type (U-tube, shell-and-tube or other).

Heat-transfer area; length, number, and diameter of tubes.

Tube material.

Counterflow or parallel flow.

Number and type of baffles.

Number of tube passes.

Shell material.

Manufacturer.

Types of fluids used (liquid water, steam).

2. Use detailed drawings of a main condenser (provided by instructor); draw a simplified diagram; identify all important components.
3. Connect a small shell-and-tube, parallel-flow heat exchanger to a laboratory hydraulic piping loop; measure temperature in (t_{in}) and t_{out} over a wide range of cooling-water flow rates; record results on Data Table 10-4-1; plot Δt_{hot} versus Δt_{cold} , and interpret results. Repeat this exercise by using a counterflow heat exchanger. Explain which system is more efficient.



DATA TABLE

DATA TABLE 10-4-1

Flow Rate Gal/Min	t_{in} , °F	t_{out} , °F



REFERENCE MATERIALS

LaMarsh, John R. Introduction to Nuclear Engineering.

Reading, MA: Addison-Wesley Publishing Co., 1975.

Lish, Kenneth C. Nuclear Power Plant Systems and Equipment.

New York: Industrial Press, 1972.

For information on the latest developments in reactor design, contact the following vendors:

The Babcock and Wilcox Company
Lynchburg, Virginia

Combustion Engineering, Inc.
Windsor, Connecticut

General Atomic Company
San Diego, California

General Electric Company
San Jose, California

Westinghouse Electric Corporation
Pittsburgh, Pennsylvania

(MSBR) Oak Ridge National Laboratory
Oak Ridge, Tennessee



Describe or give an example of each of the following heat exchangers (as used in a nuclear-fueled power plant):
Shell-and-tube.

U-tube steam generator.

Once-through steam generator.

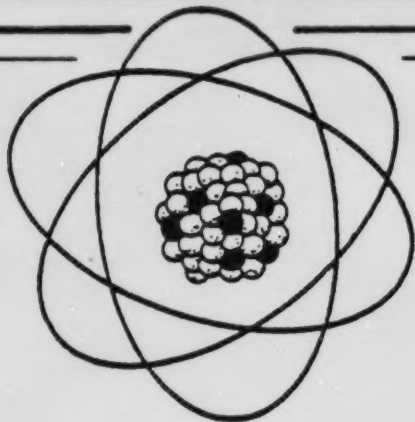
Main condenser.

Feedwater heater.

Cooling tower: Natural-draft.

Mechanical-draft.

Spray ponds.

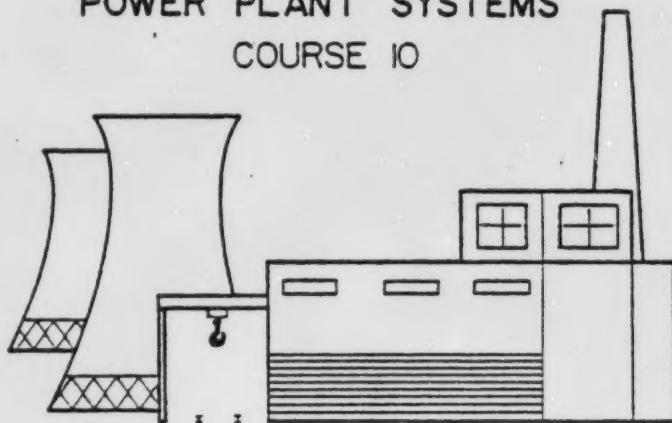


NUCLEAR TECHNOLOGY

MODULE 10-5 PUMPS. -

GERALD C. WALLACE

POWER PLANT SYSTEMS
COURSE 10



TEC-SW

TECHNICAL EDUCATION RESEARCH CENTER — SOUTHWEST
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COURSE MODULES

COURSE 10 POWER PLANT SYSTEMS

- 
- MODULE 10-1 Power Plant Fundamentals
 - MODULE 10-2 Power Plant Thermal Cycles
 - MODULE 10-3 Turbines and Generators
 - MODULE 10-4 Heat Exchangers and Condensers
 - MODULE 10-5 Pumps
 - MODULE 10-6 Valves and Piping
 - MODULE 10-7 Electrical Transmission and Distribution Systems
 - MODULE 10-8 Power Plant Fundamentals (Fossil-Fuel Energy Efficiency)
 - MODULE 10-9 Fossil Plant: Auxiliary Discussions

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Technical Education Research Center
Southwest
4201 Lake Shore Drive, Suite 111
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INTRODUCTION

The basic principle of a steam power plant is the transfer of energy from one point to another with water in the vapor (or liquid) phase as the transfer medium. Many pumps, throughout the plant, move this main energy-medium and provide cooling to components, lubrication for rotating equipment, chemicals for treatment systems, fuel oil for diesel engines and general transfer of a variety of other fluids.

The basic reactor coolant system on a pressurized water reactor contains three major components:

- Reactor (including pressure vessel).

- Steam generator.

- Reactor coolant pumps.

About thirty pumps operate in a reactor coolant system. And from 100 to 150 pumps, in a modern steam power plant, are not unusual; thus, a basic knowledge of pumps (for prospective power plant operators) is in order.



MODULE PREREQUISITES

The student should have completed the following modules: 4-1, "Basic Properties of Fluids," 4-2, "Fluid Statics," and 4-3, "Fluid Dynamics."



OBJECTIVES

Upon completion of this module, the student should be able to:

1. List the three major types of pumps and give at least three examples of each from this module.
2. List pump components and discuss function of each component.
3. Determine at least four of six pump characteristics from literature or lab experiments.
4. Given a typical pump system, select most appropriate type of pump(s) for job.
5. Use a typical pump or pumps to determine the following characteristics: flow, head, power requirements and net positive suction head.
6. Disassemble a typical pump; identify all parts; reassemble in correct working order.



PUMP TYPES

A large number of pumps may be used in a nuclear power plant (or any power plant), but more significant than quantity of pumps is variety; they vary greatly in size, types of fluid handled, prime moving power and principles of operation.

This discussion evolves around three basic classes of pumps (and several specific types within each class):

Centrifugal.

Rotary.

Reciprocating.

Most pumps in use today fit into the centrifugal class.

CENTRIFUGAL

Different types of centrifugal pumps include:

Volute (the majority of pumps built today) - available as horizontal or vertical, single- or multi-stage, and for wide ranges of flows and pressures.

Diffuser - used frequently as multi-stage, high-pressure units.

Mixed flow (usually vertical, with single-inlet impeller) - ideal for low-head, high-capacity applications.

Axial flow (also called propeller pumps) - usually vertical; best suited for low-head, large-volume applications; these pumps develop most of their head with lifting action vanes.

Turbine or regenerative (horizontal or vertical) - these low- to medium-capacity, high-head pumps fill a gap

between other centrifugal pumps and the rotary class.

ROTARY

Rotary class pumps include:

Gear, which uses two or more meshing gears (spur, single or double helical teeth).

Vane (a series of vanes, blades or "buckets" turned by a single rotor) - includes lobe or shuttle-block design.

Cam and piston (like most rotaries, a positive displacement pump).

Screw (two parallel shafts with meshed screw "threads" running full length) - works well with nonabrasive, viscous fluids.

RECIPROCATING

These simple piston pumps use different methods of driving:

Direct acting (steam is applied to and exhausted from piston at one end of shafts to supply power to force water out of the pump end).

Power (driven externally through a crankshaft or other device).

Crank (uses flywheel - as distinguished from eccentric - as its drive mechanism).

CENTRIFUGAL PUMPS

The workhorses of power plants, centrifugal pumps, excel at moving water, oil and most other fluids.

PRINCIPLE OF OPERATION

The first thing to understand is the principle that makes such a pump functional (Figure 10-5-1). The example

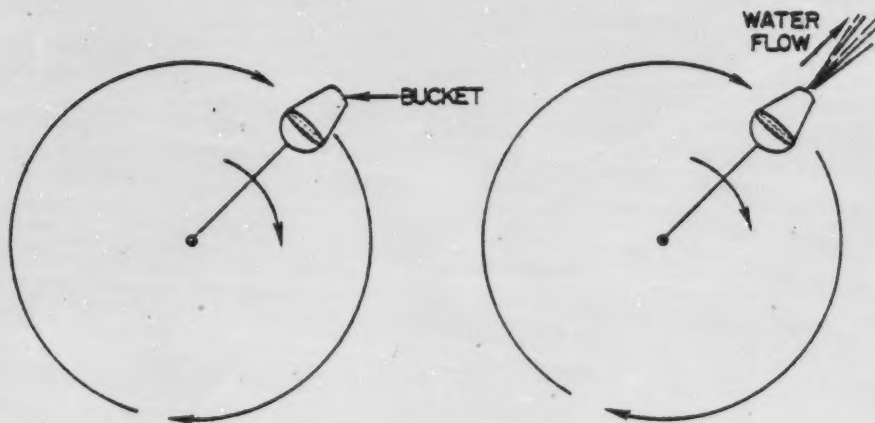


Figure 10-5-1. Centrifugal pump operating principle.

used is the childhood experience of holding a bucket of water and swinging it around in an arc overhead. The water stays in the bucket despite its upside down position. Probably everyone has tried this stunt, and most have learned that water was held in the bucket by "centrifugal" force. Any object (including a molecule of water) moved in a circle exerts an outward force related to the mass of the ob-

ject and speed at which it is traveling; taking this simplified model a step further, let a hole in the bottom of the moving bucket simulate a crude centrifugal pump. As the bucket arcs, water shoots out the hole, with distance covered being a direct function of speed of the bucket. For pump application, some means of directing the fluid where it is wanted, as well as a source of fluid input so that operation can be continuous, must be provided.

TERMINOLOGY

Head is the pump term used to measure height of the stream of water from bottom of bucket, and for measuring pump output. Specifically, head is the pressure increase resulting from the work applied to the fluid by the pump. Generally, head is measured in feet of water. A pump supports a column of water in its discharge equal to its design head plus any supply pressure applied. Take, for example, a pump connected to a reservoir (for its supply), with reservoir level 10 feet above pump (Figure 10-5-2), and pump

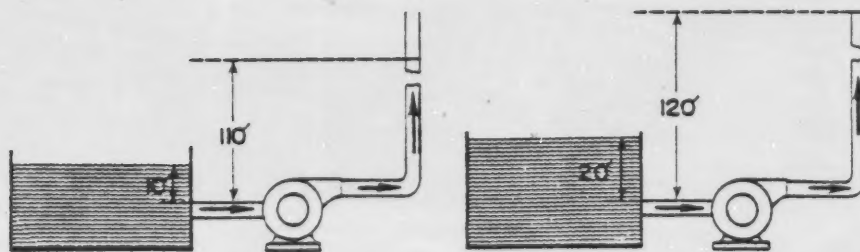


Figure 10-5-2. Pump pressure increase: head plus supply pressure.

outlet connected to a long, vertical, open pipe. If the pump, rated at 100 feet of water t_{dh} (total developed head, or shutoff head), were started, shortly there would be no flow in the system, but water level in pipe would be 110 feet above pump. The pump has increased pressure from 10 feet at its suction to 110 feet at its discharge by exerting into the water all the work of which it is capable. Note that water level (head) could be raised by increasing water level of the reservoir, or by increasing pump speed.

Other pump terms are defined here as follows:

Pumping is addition of energy to a liquid to move it from one point to another. As noted above, the head it develops is the form this energy addition takes and is one criterion by which proper pump selection is made. If the example system only needed to lift the water 30 feet, a more suitable pump, with less head, should be selected.

CENTRIFUGAL PUMP CONSTRUCTION/FUNCTION

Centrifugal pumps employ centrifugal force to develop a pressure increase for moving a liquid.

Construction

Impeller is the rotating element inside a centrifugal pump through which liquid passes and by means of which energy is imparted to the liquid (there are many designs and applications for pump impellers).

Casing of a centrifugal pump is the housing surrounding the impeller. It contains bearings that support the shaft on which impeller is mounted. The "bucket" example had no water-tight casing, so output was not adequately

controlled as in a real pump.

A single-stage centrifugal pump, as the name implies, has only one impeller.

A multi-stage centrifugal pump is one having two or more impellers on one shaft acting in series within the casing. The word "series" is a vital concept of the multi-stage pump because adding an additional series impeller increases head of the pump, not flow. As shown by the reservoir model (Figure 10-5-3), output of the pump at the 110-foot level

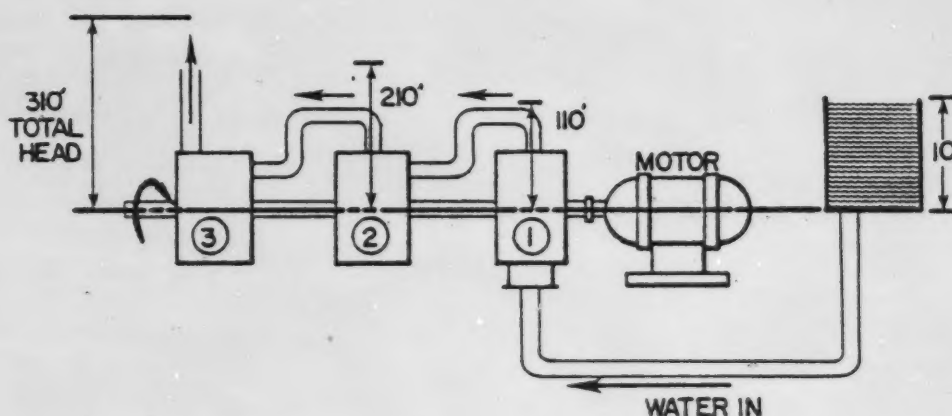


Figure 10-5-3. Net effect of three pumps in series.

could be piped into the suction of an identical pump and pumped to 210 feet (310 feet for a third pump, and so on). The pump impellers, which increase the head incrementally, may be on different pumps or fluid may be routed from discharge of one impeller to suction of the next, all within a single casing.

Function

Pressure is force exerted per unit area of a fluid (Figure 10-5-4). Common units are psi (pounds per square

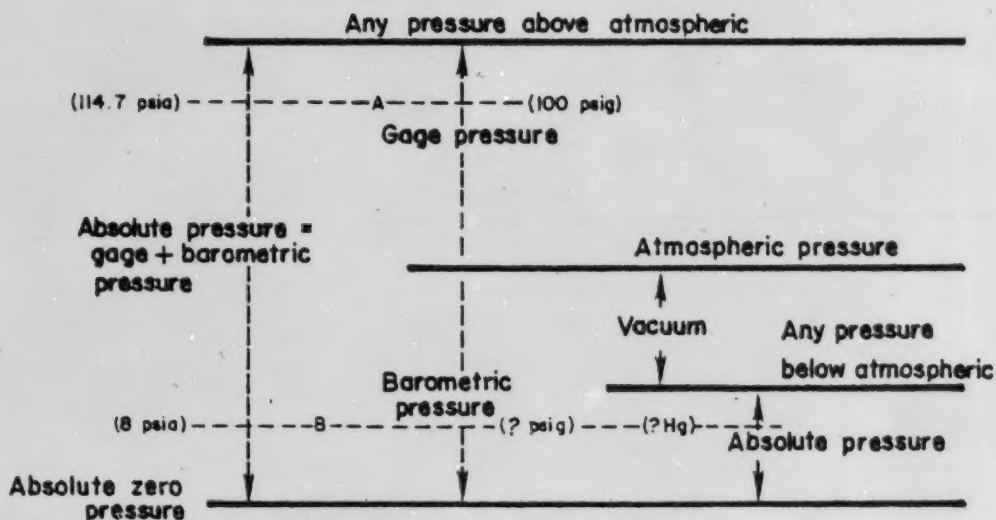


Figure 10-5-4. Relationship between various pressure terms used in pumping.

inch). This basic unit of measurement, commonly expressed in several manners, is based upon a specific atmospheric pressure reference. The atmosphere itself places a static pressure on all exposed surfaces of 14.7 psi at sea level, and this pressure must be accounted for when making measurements and calculations on pump performance.

Gage pressure is pressure measured at a given point related to atmospheric pressure.

Absolute pressure is the pressure above absolute zero - it may or may not be greater than atmospheric pressure.

Vacuum is a pressure less than atmospheric, and is normally measured in inches of mercury (Hg).

EXAMPLE

Point A (Figure 10-5-4) is 100 psig (gage), which means that the same point is 114.7 psia (absolute). Point B is 8 psia. Clearly this pressure is less than 0 psig and, as a method of measurement, of no value. Normally, pressures in this range are expressed in inches of mercury (Hg) vacuum, or absolute pressure. If Point B is at 16 inches Hg vacuum, pressure is less than atmospheric by the pressure equal to 14 inches of mercury. (This area may be a little confusing, but student is encouraged to master the relationships now. Pressure in a main condenser, for example, may be expressed in both absolute and vacuum units and this pressure, plus height of water in the condenser, defines suction pressure to condensate pumps.)

Vapor pressure is the pressure - for a given temperature liquid - at which the liquid is in equilibrium with the atmosphere (or its own vapor in a closed container). If temperature is increased or pressure reduced, the liquid will begin to vaporize. Example: vapor pressure (or boiling point) of water at 60°F is 0.256 psi; at 212°F it is 14.7 psi.

Net Positive Suction Head

Net positive suction head (npsh) is a measure of the head of liquid at the suction of a pump compared with the

vapor pressure. It is calculated by the formula:

$$\text{npsh} = \text{hs} + \text{ha} - \text{hvp} \quad \text{Equation 10-5-1} \\ (\text{Equation} = \text{Eq.})$$

where

hs = total suction head.

ha = atmospheric pressure.

hvp = vapor pressure.

A pump must have a positive value for this calculation or liquid will vaporize at center of impeller, which is the lowest pressure point. If vaporization occurs, vapor bubbles move along vane surfaces until pressure builds up and the bubbles collapse (called "cavitation," and very destructive to metal parts - forming and collapsing of the bubbles causes extreme turbulence and erosion of impeller and casing). If cavitation becomes extreme, all the fluid may vaporize, causing pump to become "vapor bound" and cease to pump. When a pump is cavitating, it sounds as if it is full of stones or marbles.

A couple of sample calculations (a reactor coolant pump and a condensate pump) illustrate the point adequately.

EXAMPLE

Reactor coolant pump:

$$\text{npsh} = \text{hs} + \text{ha} - \text{hvp}.$$

hs = total suction head = applied pressure (assume 2150 psi) + height of water (assume 40 feet and convert that to approximately 20 psi). To keep this calculation simple, assume no friction losses (they do exist and increase with flow, causing a lessening of npsh with flow, as will be seen when performance curves are studied later in this module).

$$\text{ha} = 14.7 \text{ psi (assume 15 psi)}.$$

hvp = vapor pressure (assume reactor coolant temperature of 530°F and a corresponding hvp of approximately 900 psi).

$$\text{npsh} = 2150 + 20 + 15 - 900 = 1285 \text{ psi}.$$

EXAMPLE

Condensate pumps are much more of a problem; they are prime candidates for cavitation.

$$\text{npsh} = \text{hs} + \text{ha} + \text{hvp}.$$

hs = 4 feet of water back pressure (assume 26 inches of Hg vacuum). (Do your calculations give the same applied pressure for this assumed vacuum?) ± 8 feet of water due to distance between hotwell and eye of impeller.

ha = 0: This system is under vacuum, and atmospheric pressure is not applied to the water.

hvp = 4 feet of water. This pressure will almost certainly be the case because the condenser is

a closed container with the fluid changing from vapor to liquid state, so fluid will be in an equilibrium state. (It is possible to subcool condensate a few degrees; however, assume saturation condition.)

$$npsh = (4 + 8) + 0 - 4 = 8 \text{ feet of water.}$$

A good operator checks condensate pumps for cavitation frequently, as head loss caused by pipe friction and configuration can reduce this value of npsh near to cavitation point.

PUMP TYPES

Centrifugal pumps rely upon any one of the basic pump designs:

Impeller.

Propeller.

Turbine drive.

Impeller

Impeller designs for centrifugal pumps are almost as numerous as their applications. They all have vanes spiraling out from the center for fluid to move along as it picks up energy. Vanes may be in an open, semi-open or closed arrangement (Figure 10-5-5). Impeller A, which has vanes attached to a central hub, with only a small shroud on one side, is an "open" impeller. Impeller B, however, has a complete shroud on one side and is, therefore, only "semi-open." Impellers C and D, with vanes totally enclosed

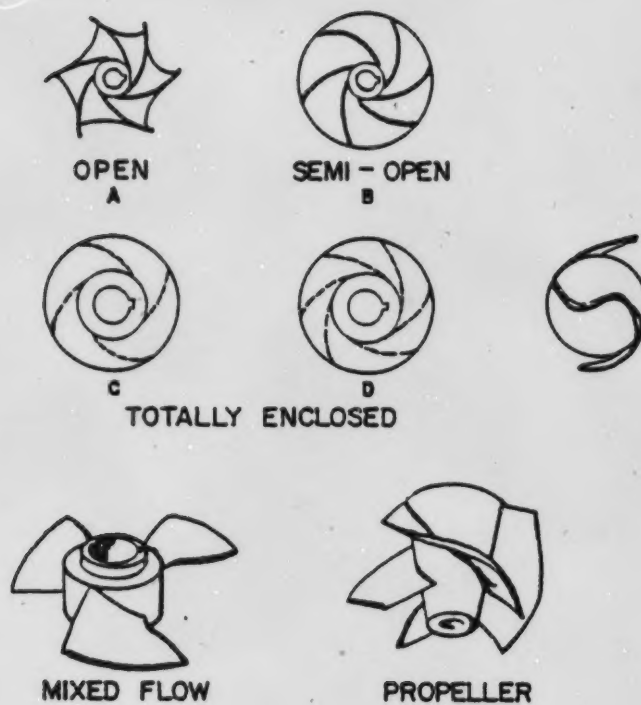


Figure 10-5-5. Centrifugal pump impeller designs.

by shrouds on both sides, allow water to enter only from the right (C) or from both left and right (D). Most pumps in power plants have closed impellers.

The simplest and most common centrifugal pump casing is the volute (Figure 10-5-6); a progressively expanding

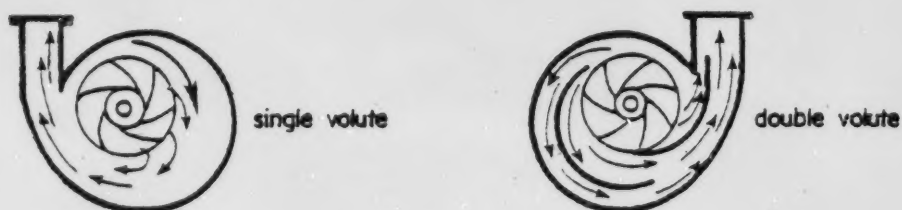


Figure 10-5-6. Typical volute pump section.

casing surrounding the impeller gradually reduces fluid velocity and increases its static pressure.

Since parts are minimized, construction costs are low; however, the pump itself is very efficient.

A diffuser (Figure 10-5-7), simply a set of station-

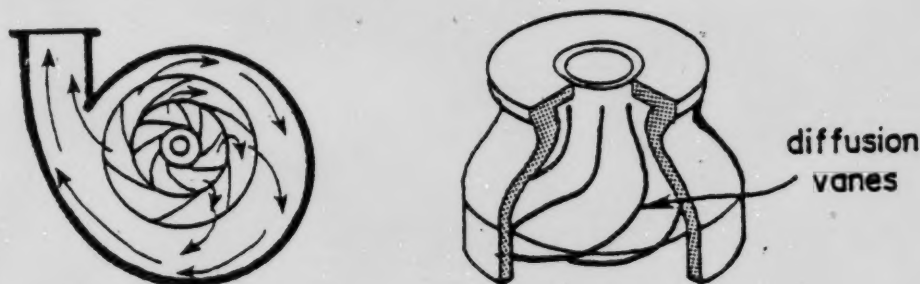


Figure 10-5-7. Diffuser-type centrifugal pump design.

ary blades surrounding the impeller to redirect flow and essentially act as small volutes, balances forces across the pump shaft. These diffuser-type pumps exhibit more stability than simple volutes, and bearing life should be increased because both shaft and impeller remain closer to their center of rotation.

Areas of pump casing and impeller that provide the seal between low-pressure suction water and high-pressure discharge water are particularly susceptible to wear if the shaft moves; thus it has to be a "touch" fit to prevent water from cycling between discharge and suction. On most pumps, this area of the impeller housing contains wear rings (Figure 10-5-8), which allow replacement of small inexpensive parts rather than replacement of entire impeller or casing.



Figure 10-5-8. Six types of centrifugal pump wear rings.

Propeller

Another type of centrifugal pump is the propeller type, which obtains most of its flow by the lifting or pulling action of propeller vanes. The simplest example of this type pump is a common window fan. As the blades rotate through the fluid (air in our example) the angled blades "bite" into the fluid and exert pressure on it. Most pumps of this type are vertical and have low heads but high capacity (flow rates).

Mixed-flow pumps combine volute and propeller characteristics; that is, impeller vanes pump by using both the centrifugal force of a volute pump and the lift of a propeller pump.

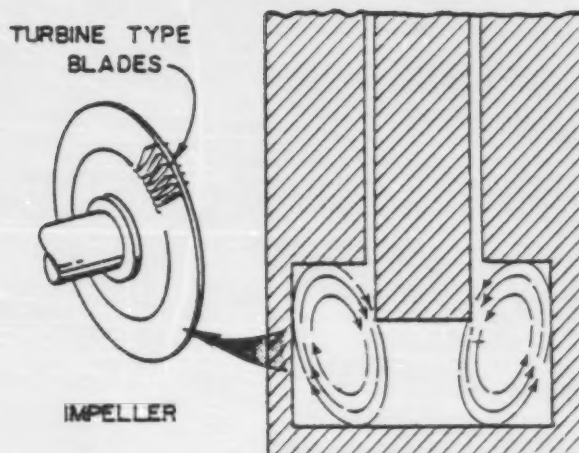
Turbine Drive

Turbine type pumps, so called because the impeller looks like a steam turbine blade (Figure 10-5-9), have many short blades that travel around in an open annulus. Water travels almost a full circumference while in contact with the blades, and energy is transmitted by a series of impulses.

PERFORMANCE

To measure pump performance, a graph of its most important parameters (called pump performance curves) is

Figure 10-5-9.
Turbine-pump impeller.
(Inset illustrates
impulse blade action.)



available. Coordinates of the curve are "head" and "flow"
(Figure 10-5-10). Note that point A shows zero flow, and

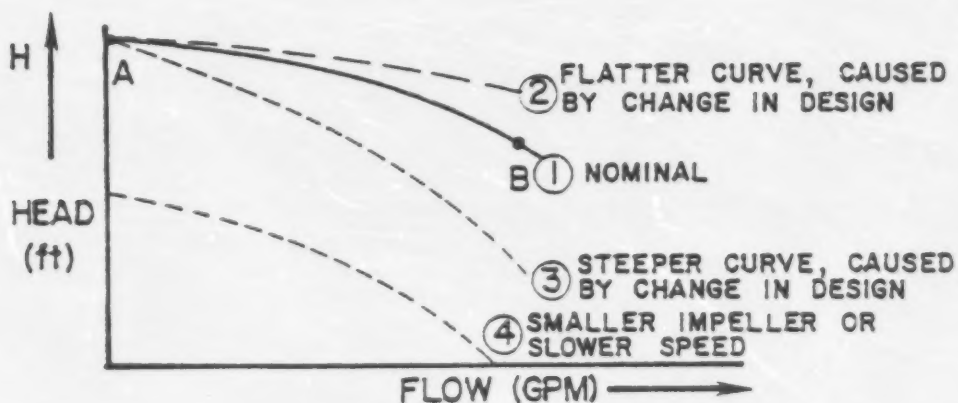


Figure 10-5-10. Centrifugal pump performance curves.

the highest head, indicating maximum pressure increase of which a pump is capable. Also, if a pump operates at this

point, it overheats, which decreases its life expectancy.

Point B, called "runout," is not nearly as well defined as point A, but is just as bad operationally. This condition is such that pressure drop of the system is inadequate to restrict flow and the pump freewheels, drawing a large electrical current. That is, fluid flows through the pump because of operations of other pumps in system, which causes the impeller to rotate. Such a condition might exist when starting a pump to fill a large system, particularly in a system that normally uses two or more pumps operating in parallel. For this reason, centrifugal pump startup generally occurs with closed discharge valves. Operating two pumps in parallel tends to increase head on both as they tend to oppose each other - their available area for flow is half what it would be for one pump alone. In a reactor plant, for instance, normal pump flow, with all four reactor coolant pumps running, is about 100,000 gpm/pump; but, if two pumps are shut down, the other two can each put out about 150,000 gpm.

While curve number 1 would be representative of a typical pump, numbers 2 and 3 can be obtained if some basic changes occur in impeller design. Several things can be done to produce a flatter curve (number 2), such as making blades of the impeller wider - this increased volume of the impeller supplies the system more easily. Increasing number of vanes on the impeller also can produce the same result, as will decreasing pitch of the vanes. Making the impeller narrower, with less vanes, or giving the vanes greater pitch should result in curve number 3. Shutoff head remains the same for all these modifications because it is essentially dependent upon vane tip speed. Reducing diameter of impeller produces a similarly shaped curve, but one

of lower head characteristics at all points (curve number 4).

Most pumps today are driven by constant-speed motors; however, some are driven by variable-speed motors and steam turbines, producing yet another family of curves (e.g., a curve for each 200-rpm change through the operating range). Curve number 4 results from either a smaller impeller or a slower speed for the same impeller.

Basic pump curves then, are simple to understand. Pump efficiency may be shown in two different ways: 1) a family of efficiency curves for a family of pumps or 2) a specific curve for a specific pump (Figure 10-5-11).

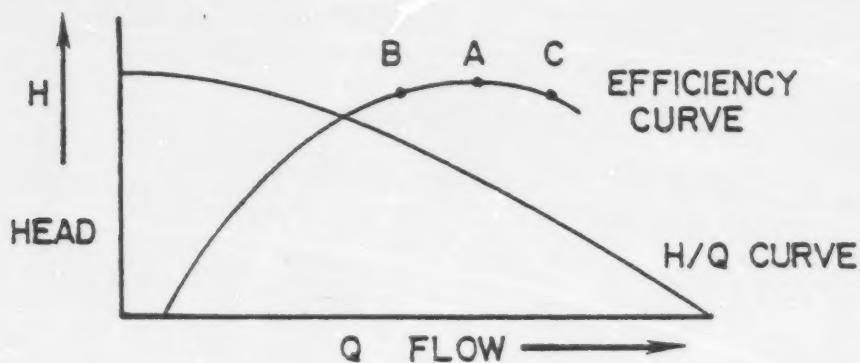


Figure 10-5-11. Specific pump curves.

Looking at the individual curve, it becomes apparent that point A is most efficient for the particular pump speed, but operation can be satisfactory between points B and C. (Note: A "family" of curves shows the same type of information.) Operation out of range B-C is more costly and pump life can be shortened. Thus, curve information allows an operator to make better decisions about bringing on a

second pump during startup, or taking off an extra pump when shutting down.

Brake horsepower (bhp) is also shown for individual curves (Figure 10-5-12). For the individual pump, bhp

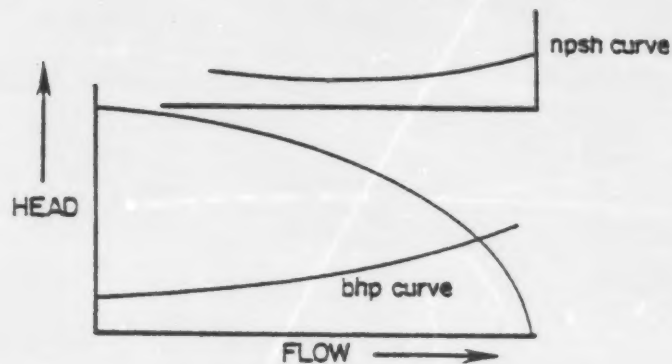


Figure 10-5-12. Individual performance curve, showing brake horsepower (bhp) and net positive suction head (npsh).

simply plots as a gradually increasing curve from shutoff head up to full runout of the pump. (A family of curves requires a family of bhp curves.)

It is not surprising to see npsh (net positive suction head) requirements increase as flow increases. But recent developments in large pumps for large power plants show that low flows also require higher npsh to prevent cavitation damage (due to high recirculation flows within the confines of the impeller itself).

ROTARY PUMPS

Rotary pumps employ an entirely different method to apply pressure to fluid to be moved. A major difference is that most rotary pumps use positive displacement, which means that a like amount of fluid is pumped each revolution or stroke regardless of discharge pressure; that is, discharge pressure will only be as high as required to overcome system resistance.

It was pointed out that centrifugal pumps often are started with discharge valves closed. This procedure would invite disaster to a rotary pump - it would burst the casing. In fact, a rotary pump should have a relief valve on its discharge to prevent such damage.

PRINCIPLES OF OPERATION

Rotary pumps operate primarily on three principles.

First, inner surfaces of pump casings are finely machined to provide a seal surface for rotating components to work against as they pressurize the fluid. Rotating elements of many of these pumps consist of meshing lobes, screws or gears, which pick up fluid in the space between meshing components and carry it to discharge port.

Second, a single rotor with a center of rotation off center from the housing, termed "eccentric," picks up fluid from the largest space in the casing and transports it around the casing into the smaller space, putting pressure on the fluid. The rotating element must have movable vanes or some such arrangement to allow float out and in, maintaining a seal against the housing and forming boundaries for the

variable-sized chamber.

Third, screw pumps, like lobe pumps, depend on finely meshed sealing surfaces to force fluid through the pump. These pumps have meshing threads along their shafts that force fluid along shaft into discharge port.

CONFIGURATIONS

General configurations of the most common rotary pump design types are presented below.

External gear pumps (Figure 10-5-13) are the simplest

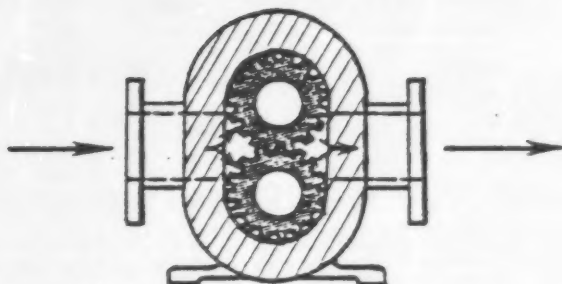


Figure 10-5-13.
External gear pump.

rotary type. Liquid first fills spaces between gear teeth as they separate on the suction side. Then it is carried around and squeezed out as the teeth mesh again. Pump gears may have spur teeth, single-helical teeth or double-helical teeth. Some designs also include a drilled idler to reduce internal thrust.

Lobular pumps (Figure 10-5-14) resemble gear pumps in action, but use rotors rigged with lobes (two, three, four

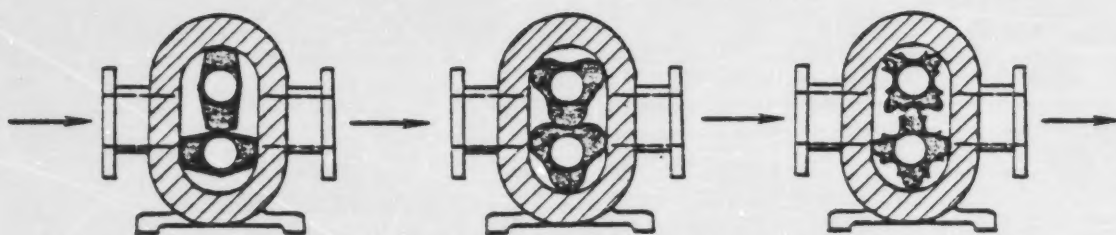
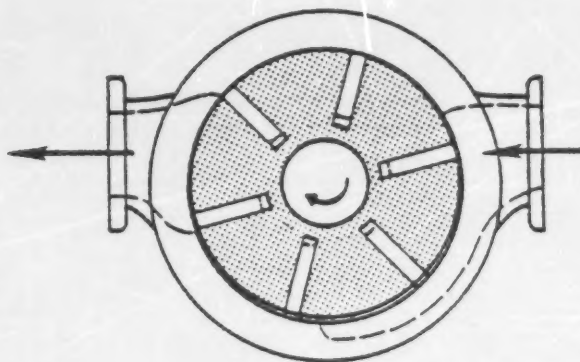


Figure 10-5-14. Lobular pumps.

or more). The rotors are synchronized for positive and precise rotation by external gears.

Sliding-vane pumps (Figure 10-5-15) use vanes that

Figure 10-5-15.
Sliding-vane pump.



sling out against the casing bore when pump rotor turns. Liquid is carried around and forced out discharge.

Eccentric pumps (Figure 10-5-16) produce pumping action by squeezing the flexible rotor against the housing to force liquid out the discharge.

Single-screw pumps (Figure 10-5-17) employ a spiraled metal rotor, which turns eccentrically within a rubber helix

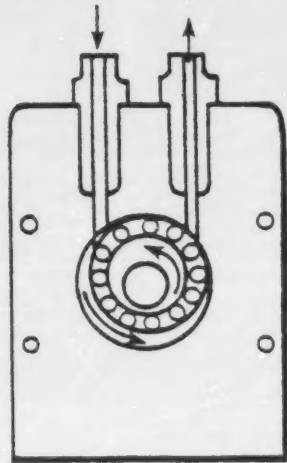


Figure 10-5-16.
Eccentric pump with
flexible chamber.

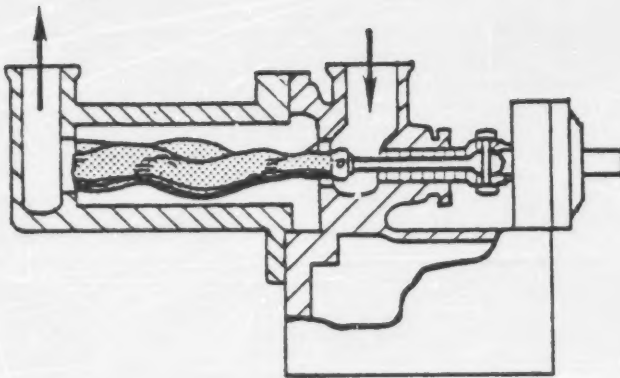


Figure 10-5-17.
Single-screw pump.

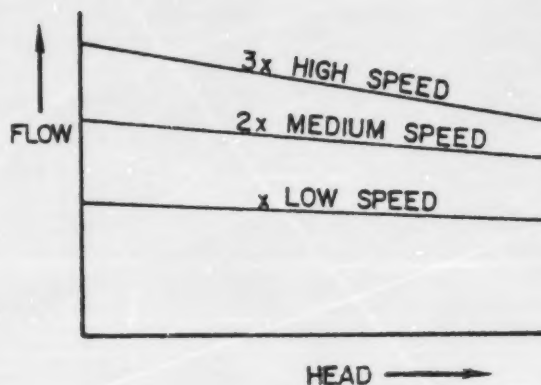
stator (or liner). Double- and triple-screw pumps use one or two idlers, respectively. Liquid flows between the screw threads along the screw axis. Opposed screws eliminate end thrust.

PERFORMANCE

Curves for rotary pumps differ considerably from the

centrifugal type because they are positive displacement. These curves will not be perfectly flat (due to leakage past sealing surfaces at higher pressures, called "slip"), but the variance is slight indeed. A family of curves (Figure 10-5-18) could be produced only by different speeds of the pump, with higher speeds producing higher flows and a little more slip.

Figure 10-5-18.
Family of curves for different pump speeds.



RECIPROCATING PUMPS

The simplest of all pumps to understand, the reciprocating type employs pistons that move back and forth within a cylinder (Figure 10-5-19). These pumps also produce positive displacement - everything in the cylinder will move out somewhere when the piston moves.

Nuclear plants of today utilize these pumps where high heads and relatively low flow rates are needed - primarily in two ways:

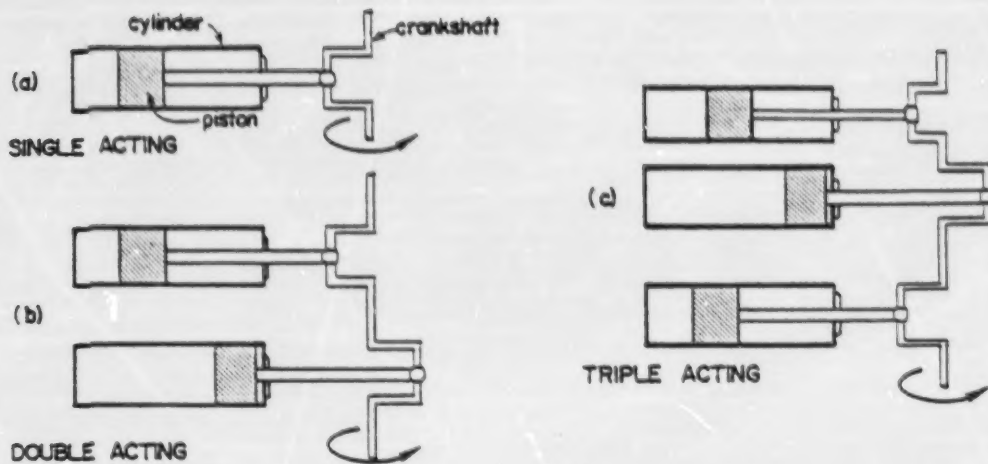


Figure 10-5-19. Reciprocating pumps: 1-, 2- and 3-cylinder designs.

as charging pumps (water into reactor coolant for makeup, and to reactor coolant pump seals to keep them cleaned and cooled).

as chemical metering pumps (chemicals to systems at very low rates with precise volume control).

The pumps usually have a variable stroke to allow accurate injection rates. Charging pumps normally use three pistons, operating sequentially, to reduce pulses in the lines and to attempt to hold a steady discharge pressure. The latter reduces fluctuations, but a pulsation dampener often must be employed to cushion shock to the system. The dampener is a dome containing a diaphragm with water from discharge header of pumps on one side and nitrogen on the other. The diaphragm flexes inward with each stroke of the pistons and outward between strokes, acting like

a hydraulic accumulator. Even with multi-piston pumps and the pulsation dampener, "hammer" noise will occur in the charging lines.

Flow rate of these pumps can be made to vary by several interesting pieces of equipment such as variable-speed motors, changing steam pressure or infinitely variable belt drive. This variable belt drive operates as follows.

The pump shaft is belt driven, and its pulleys are varied in width to change their relative size (Figure 10-5-20). The drive pulley is air loaded so that the two

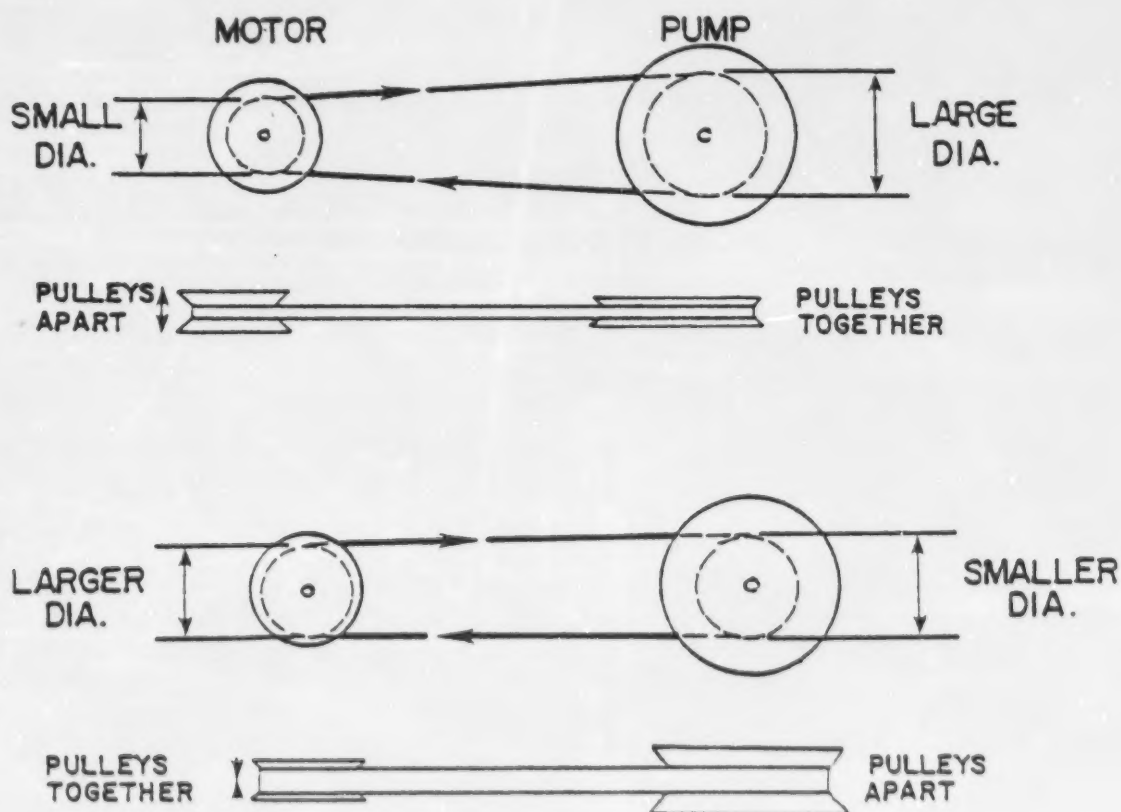


Figure 10-5-20. Pump shaft belt-drive arrangements.

halves move closer together to increase speed. When the pulley halves are closer the belt rides higher on the sides of the shives, increasing effective diameter of the pulley. The idler pulley, which drives the pump, is spring loaded to pull together as closely as possible and keep the belt tight. When drive pulley is pushed together, its effective diameter is increased, and idler pulley has to spread to reduce belt tension. Thus, its diameter is effectively reduced, and the effect is to make drive pulley larger and idler pulley smaller, which increases pump shaft rotation relative to motor rotation.

A direct-acting reciprocating pump is not likely to be found in a nuclear power plant but is fairly common to other steam plants. As noted in introductory material, reciprocating pumps differ in the manner in which the piston is caused to reciprocate, though piston operation is standard and hard to improve upon.

The double-acting steam-powered piston pump is common to many steam plants. It uses two pistons at opposite ends of the shaft. Steam is admitted to one piston, which strokes the other piston, which pumps the water. The steam is exhausted and the drive piston returned to its original position, allowing more water to enter the pump cylinder (Figure 10-5-21). Then the cycle is repeated.

Small pumps of this type are often used to inject chemicals where flow rates are low and accurately controlled. Methods of varying capacity usually are nothing more than methods for varying stroke length. Most of these pumps also use diaphragms deflected by oil to force out fluid. The nature of these chemicals makes a noncorrosive diaphragm the logical interface, rather than a machined cylinder-to-

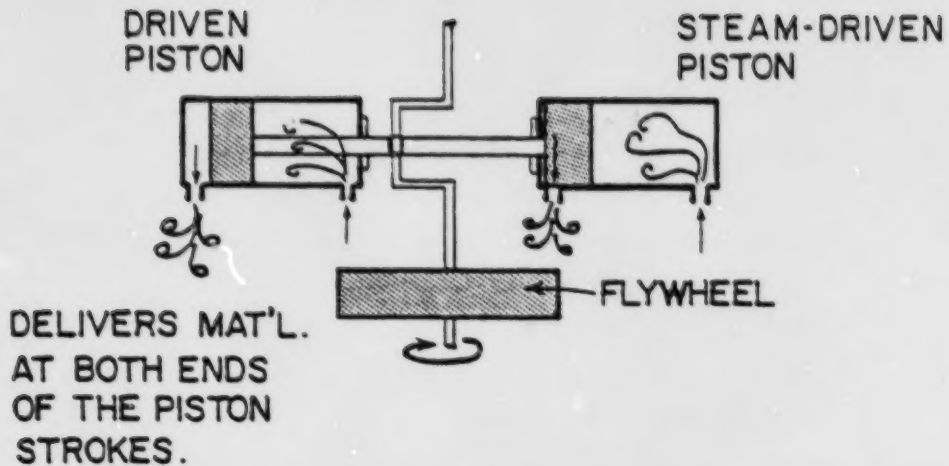


Figure 10-5-21. Double-acting steam-powered piston pump.

piston interface. In an ideal situation, the piston displaces the oil, which deflects the diaphragm, which displaces the chemical.

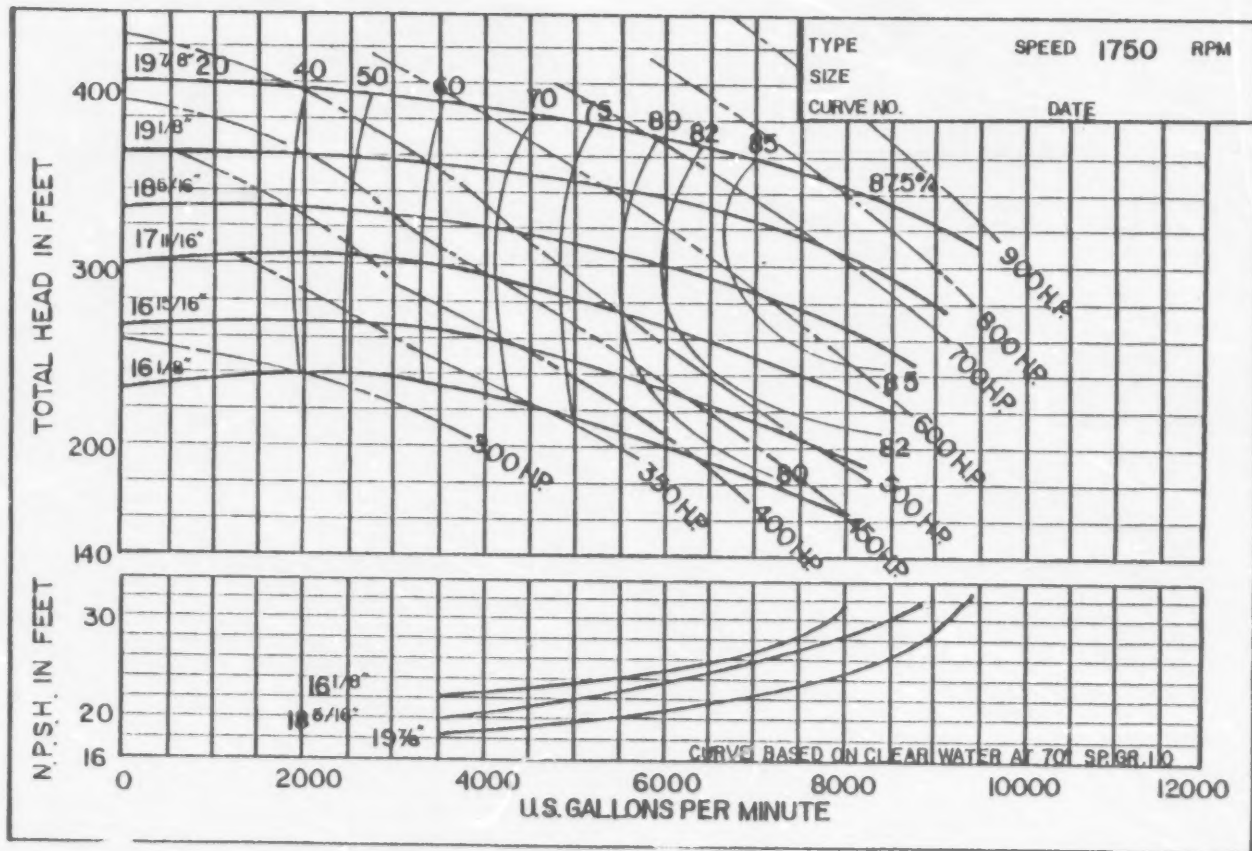


EXERCISES

Use pump performance curves I and II (Figures 10-5-22 and 10-5-23); answer the following questions:

1. What is maximum head developed by pump for each size

Figure 10-5-22. Typical pump performance curves I.



END SUCTION CHEMICAL PUMPS
1150 RPM

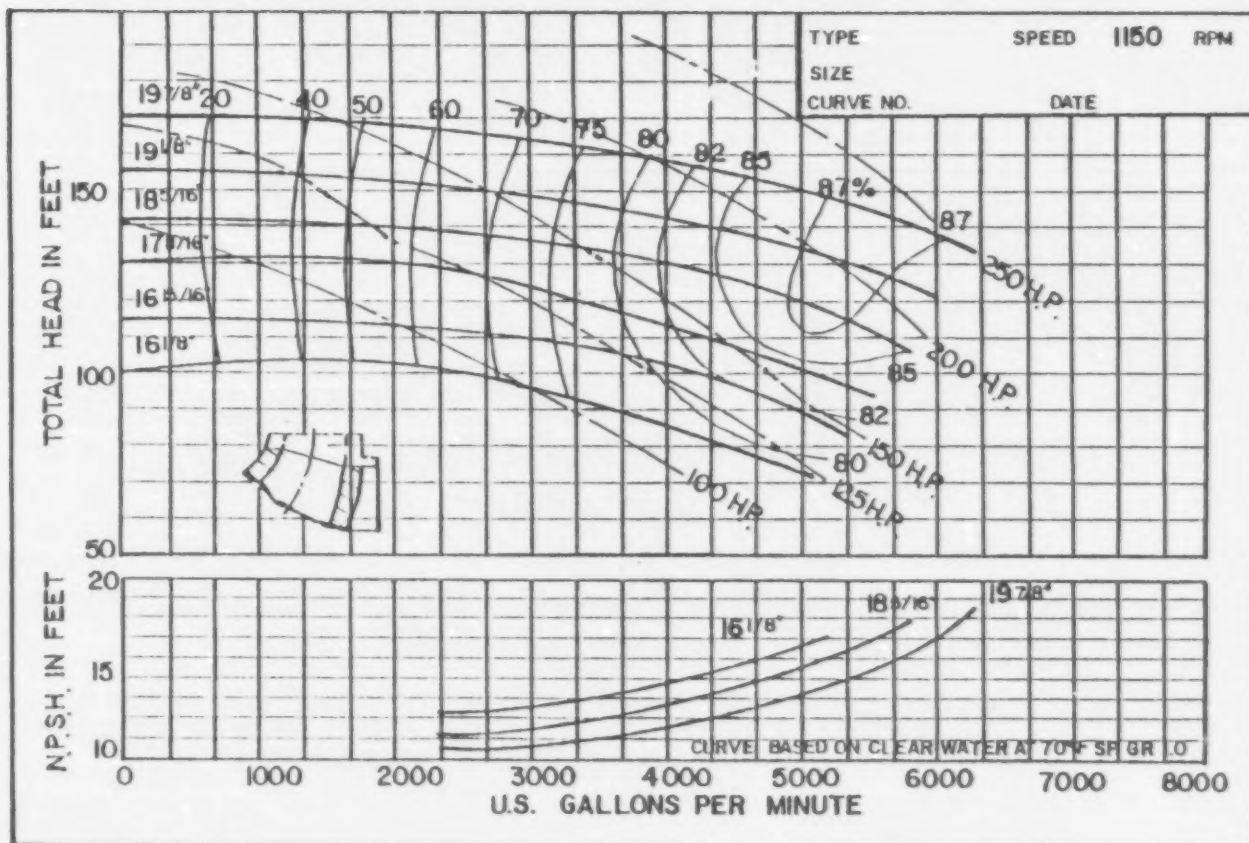


Figure 10-5-23. Typical pump performance curves II.

- of impeller and pump speed? (Record answers on Data Table 10-5-1.)
2. What is peak efficiency of 17-11/16 inch diameter impeller at both 1750 and 1150 rpm?
 - 1750 rpm
 - 1150 rpm
 3. How many of these impellers can supply 4000 gal/min against a head of 260 feet?
 4. How much water will each impeller size deliver at an npsh of 26 ft, 0 in?
 - a.
 - b.
 - c.
 5. Plot a point on curve at 5000 gal/min and 260 ft total head.
 6. Which impeller size should be used for this application?
 7. What will its efficiency be?
 - B =
 - C =
 8. What is required npsh for each impeller delivering 6000 gal/min?
 - a.
 - b.
 - c.
 9. What is difference (in motor horsepower and rpm between a pump delivering 4000 gal/min against a total head of 100 ft and a pump delivering 4000 gal/min against a head of 300 ft?
 - a. = hp rpm
 - b. = hp rpm

10. What is maximum total head a pump will deliver against a fixed motor hp of 150 at a required efficiency of 81%?
11. List decisions to be made between installing one pump or two to deliver a total of 3000 gal/min into a total head system of 300 ft.



MATERIALS

Miscellaneous pipes, elbows, T's and threading devices.
Centrifugal pump (volute, diffuser or axial flow).
Rotary pump (gear, piston or screw).
Reciprocating pump (direct-acting).



PROCEDURES

1. Use a centrifugal pump in a simple piping flow loop. Determine - as a function of flow rate - the following:
 - Head.
 - Power requirement.
 - npsh.(Record determinations on Data Table 10-5-2.)
2. Disassemble one each of the following pumps:

Centrifugal (volute, diffuser or axial flow).

Rotary (gear, piston or screw).

Reciprocating (direct-acting).

Identify all major parts; reassemble each pump in correct working order.



DATA TABLE

DATA TABLE 10-5-1

Impeller Size	Maximum Head	
	1750 rpm	1150 rpm
a.		
b.		
c.		
d.		
e.		
f.		

DATA TABLE 10-5-2

Flow Rate (gal/min)	Head (in)	npsh (psi)	Power Requirement (hp)



REFERENCE MATERIALS

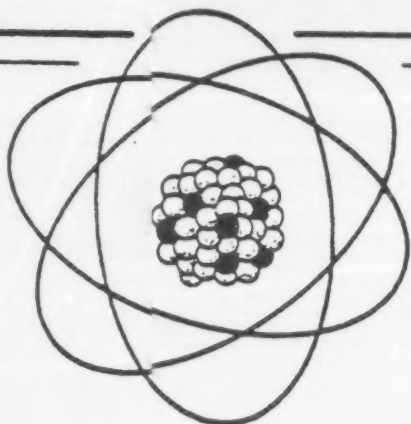
Baumeister, T. and Marks, L.S., eds. Standard Handbook for Mechanical Engineers. 7th ed. New York: McGraw-Hill, 1967.

Hicks, Tyler G. and Edwards, T.W. Pump Applications Engineering. New York: McGraw-Hill, 1971.



1. List the three major types of pumps; give three examples of each:
 - a.
 - (1)
 - (2)
 - (3)
 - b.
 - (1)
 - (2)
 - (3)
 - c.
 - (1)
 - (2)
 - (3)
2. List main pump components, as outlined in this module; discuss the function of each:
3. Given necessary pump-characteristic curves, identify at least four characteristics obtained from each:

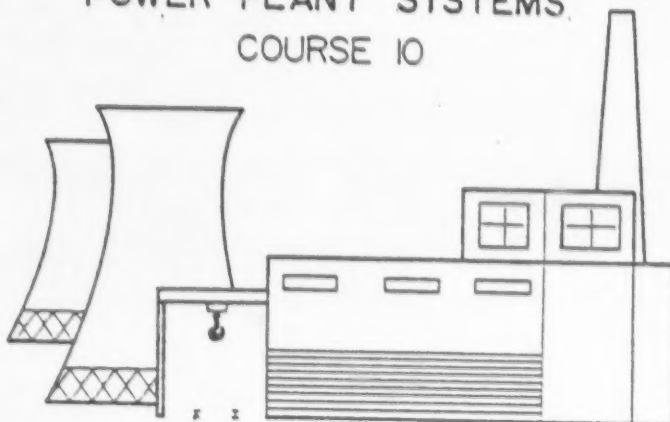
4. Given the following systems, identify particular pump you would recommend for each application:
- a. Deliver $3.6 \text{ cm}^3/\text{min}$ of additive to a chemical tank.
 - b. Pump 10,000 gal/min of water to a heat-exchanger tube side against a 200-ft head.
 - c. Deliver 8750 gal/min of heavy lubricating oil.
 - d. Deliver high viscosity grease at a rate of $9.10 \text{ cm}^3/\text{min}$ against a pressure of 2500 psig.



NUCLEAR TECHNOLOGY

MODULE 10-6 VALVES AND PIPING

POWER PLANT SYSTEMS
COURSE 10



TEC -SW

TECHNICAL EDUCATION RESEARCH CENTER — SOUTHWEST
4201 LAKE SHORE DRIVE WACO, TEXAS



COURSE MODULES

COURSE 10 POWER PLANT SYSTEMS



MODULE 10-1	Power Plant Fundamentals
MODULE 10-2	Power Plant Thermal Cycles
MODULE 10-3	Turbines and Generators
MODULE 10-4	Heat Exchangers and Condensers
MODULE 10-5	Pumps
MODULE 10-6	Valves and Piping
MODULE 10-7	Electrical Transmission and Distribution Systems
MODULE 10-8	Power Plant Fundamentals (Fossil-Fuel Energy Efficiency)
MODULE 10-9	Fossil Plant: Auxiliary Discussions

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Technical Education Research Center
Southwest
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INTRODUCTION

Nuclear power plants and their auxiliary systems carry many different kinds of liquids and gases at various temperatures and pressures. The pressure and temperature ranges are from slightly above atmospheric to well above 2000 pounds/sq in and from air-conditioning cold lines to well above 600°F (385°C). These liquids and gases must be transported, circulated and sometimes stored in various process systems. In a typical nuclear-fueled power plant, the amount of piping can be measured in miles, the number of valves in the thousands (only a few decades ago, the piping in a typical fossil-fueled power plant measured only a few hundred feet and the number of valves numbered only several dozen, or a couple of hundred).

As electrical output rating (of nuclear-fueled power plants) increases past 1000 MWe, so does systems complexity. Piping and valving in nuclear power plants are neither simple nor standard (off-the-shelf) items (except for those in drinking fountains, wash basins, showers, and the like). A majority of nuclear plant valves, especially those in the nuclear steam supply system (NSSS), must be built to very demanding nuclear specifications: they must earn their N stamp (nuclear-use approval). Likewise, the installer must be a certified welder. Once installed, valves must be maintained in accordance with strict quality assurance standards.

It becomes apparent that, with all these pipes and valves, as well as the multiple codes and standards that apply to them, a technician must have a sound knowledge of valving and piping.



MODULE PREREQUISITES

Student should understand power plant fundamentals, as presented in Module 10-1, "Power Plant Fundamentals," of this series.



OBJECTIVES

Upon completion of this module, the student should be able to:

1. List the six major valve classifications (by function).
2. Identify and describe each component or part of any valve used in a nuclear power plant.
3. Identify the two major problems associated with valve care and maintenance.
4. Identify valves according to the thirteen major generic groupings.
5. List and describe five means of actuating (operating) a valve.
6. Discuss knowledgeably the two major considerations that influence valve selection.
7. Describe the two types of valves serving "safety only" functions in a power plant.
8. List, as described in this module, the seven different basic materials from which pipes are fabricated, and describe applications of each kind of pipe.
9. Classify pipes according to pipe "schedules."
10. List, and identify by function, the major kinds of pipe fittings.



AN INTRODUCTION TO VALVES

Webster says a valve is, "Any of numerous mechanical devices by which the flow of liquid, gas, or loose material in bulk may be started, stopped or regulated..." Indeed, the complex industrial world of today uses valves of many sizes, shapes, principles and combinations of principles.

A peasant of many centuries ago must have noticed that he lost as much wine on the ground as he managed to get into his cup whenever he pulled the plug from a wine cask. With some reasoning, and incentive, he invented the plug valve - a valve so simple in design it has not changed over the years, except for materials. But, the plug valve is not the answer to all flow problems; therefore, it is important that valves be identified and classified before valve use is discussed.

VALVE IDENTIFICATION

Valves used in the NSSS (nuclear steam supply system) must be stamped with an "N" to indicate that they meet all requirements for such use as stipulated by the ASME codes as approved by the Nuclear Regulatory Commission. Qualification must be carried out by the valve manufacturer, and the "N" stamp is cut or cast into the valve housing at the factory under the strict observation and control of the code inspector or qualified factory inspector.

Valves, including those having the "N" stamp, may also carry the letters SP (for steam pressure) followed by a psia rating; e.g., PS125 indicates a steam-pressure rating

of 125 psia. Also, the letters Wog (for water, oil or gas) may be cast into the valve housing to indicate psia rating for these materials. Such letters do not intimate that a valve necessarily contains the proper interior trim to handle any of these materials, however. It may or may not. Still other valves may have other letters, such as WG for water-gas, or no letters at all. Most of these "cast" valves will not carry an "N" stamp since most NSSS valves are constructed of stainless steel.

VALVE CLASSIFICATION BY FUNCTION

The six basic functions of valves used in a nuclear power plant may be classified as follows:

Start and stop valves - usually "gate" valves - are used to start a flow process or stop it, without regard for rate of flow. These valves are usually manually operated and cheaper to buy. (They can be remotely operated.)

Regulation-of-flow valves, - used in a flow process - regulate or control the rate of flow in that stream. Generally more expensive to build, nearly all flow control is achieved with "globe" valves because flow through one is more apt to be linear, or directly proportional to the amount of opening.

Backflow prevention valves - also called "check" valves - prevent stream flow from reversing direction.

Pressure-regulation valves - ("globe" valves, generally) - reduce and maintain pressure in the flow stream. These valves operate in specified ranges: e.g., pressure reduction from 2000 psia to 500 ± 25 psia (the range, in this case, is 475 to 525 psia).

Pressure relief and safety valves protect equipment (such as pumps, tanks, pipes and heat exchangers) from overpressures. Though divided into two groups (relief and safety), construction of these valves doesn't vary much, only their uses: "Relief" valves relieve the pressure that large volumes of fluid generate; "safety" valves relieve sudden pressure, but not much volume. Safety and relief valves, often referred to as "code" valves, are specified by ASME codes. Both relief and safety valves "pop" at predetermined pressure, with the "popping" pressure being adjustable by spring pressure (above the valve stem, in most designs).

Special valves make up a nearly endless list; many, however, are described later under the heading "Generic Descriptions." Some examples include refrigeration diaphragms, metering needles, liquid metal sealed bellows, steam pressure reduction drags, tilting disc checks, and laboratory glass valves. Special valves exist wherever special applications arise.

VALVE COMPONENTS

Figure 10-6-1 illustrates a "typical" valve. It uses nearly every part found in valves, except for minor modifications and changes in nomenclature. It is shown in the closed position. As hand wheel is turned counterclockwise, the yoke bushing causes the stem to rise (because the stem cannot turn), which causes the disc to be pulled up out of the stream flow. The gland forces packing around the stem so that liquid from the stream cannot leak around it. Tightening the gland bolts forces the gland into the stuffing box

where the packing has been placed. The valve bonnet, bolted to the body of the valve, contains the upper assembly described above. When closed, the disc wedges into the seat ring, which is always attached to the body. In more expensive valves, the seat ring can be replaced; in cheaper ones, it's rolled or annealed into the body, or the base metal of the body itself may be machined to form the seat ring.

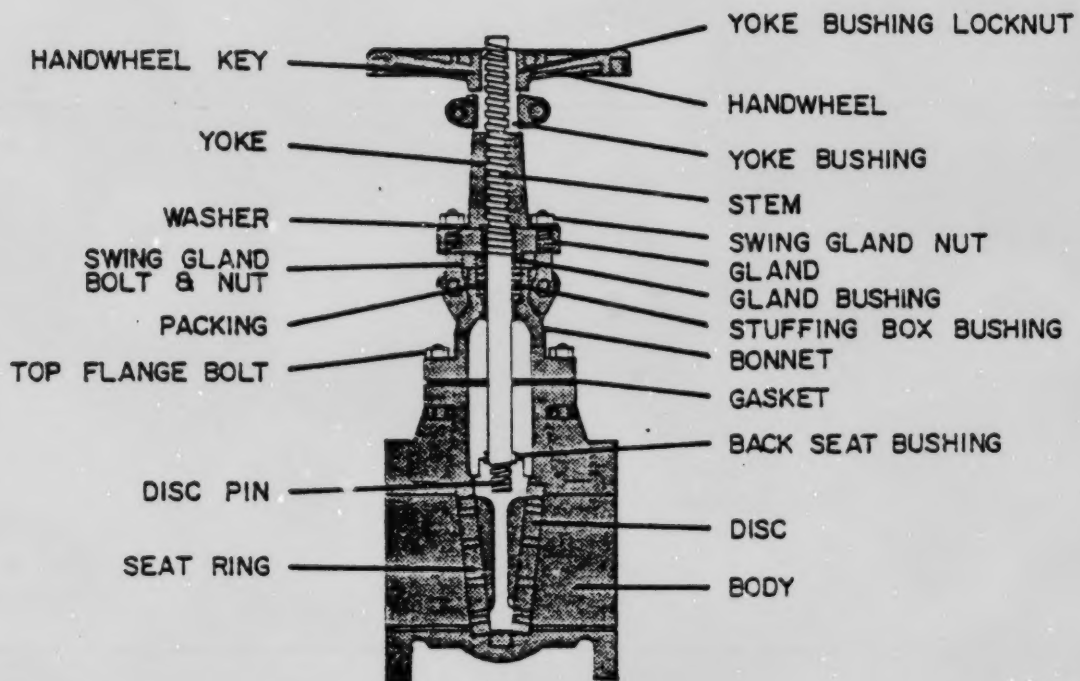


Figure 10-6-1. Typical valve, cutaway view.

Certain parts of a valve may be referred to as the trim:

Gate valve: stem, seat ring, disc.

Swing check valve: disc, disc holder, disc carrier
(or carrier pin) and seat ring.

Lift check valve: disc, disc guide, seat ring.

On more expensive valves, trim can be replaced. Replaceable trim has many advantages; e.g., it can be replaced when worn, and different kinds of trim may be placed into a valve for varied applications.

Also, more expensive valves provide the "back-seat" feature so important in high pressure nuclear systems (Figure 10-6-1). The back-seat bushing contacts the bottom area of the stuffing box bushing when valve is full open to eliminate system pressure from the packing. (System pressure creates no problem when valve is closed.)

VALVE CARE

When valves (such as the one in Figure 10-6-1) are operated, they become dry in both the packing area and the threaded stem; therefore, valve lubrication becomes important. Valves equipped with a lubricant fitting in the upper yoke utilize pressure lubricant guns. Also, most operators and maintenance people like to place a special lubricant on the stem in the area of the packing gland, usually a graphite- or molybdenum-base lubricant such as FEL-PRO or NEO-LUBE. (These lubricants ease operation of stem as it slides through the packing but do not compromise leak tightness.)

CAUTION: Never place lubricant or anti-sieze compound on a valve unless absolutely chemically compatible with process system. DO NOT USE compounds containing chlorides or fluorides.

Valve packing probably generally gives more problems than any other single item in a power plant. Thus, each application in a nuclear power plant must be "customized." Kinds of packing include asbestos, cotton, flax, linen, graphite base, teflon and many others.

GENERIC DESCRIPTIONS (MAJOR VALVE GROUPINGS)

Briefly, the valves used in a nuclear power plant were classified earlier; however, a broader discussion of the thirteen most commonly found valves deserves more specific description. Even so, such discussion must be limited to generic descriptions since each of the many brands available may offer some subtle variations or even a unique design.

Gate valves, the most widely used valves in industry, provide simple start and stop functions. When fully open, a gate valve does not restrict the process flow stream because the valve opening is as large and of the same shape as the pipe in which it is installed. Also, it can be built to withstand reasonably high temperatures and high pressures, and it can handle a variety of fluids, including water, steam caustics, acids and petroleum products. Quite reasonable in cost, the gate valve does have some drawbacks; therefore, it is not the answer to all valving problems. It cannot successfully throttle flow; its disc vibrates and rattles, and the

bottom of the disc tends to "wire draw" if throttled in a hot, high-velocity stream flow. (Wire drawing indicates an eroding of the metal at the bottom of the disc.) High-velocity stream erodes grooves in metal that give the appearance of having wires drawn across it.

Globe valves were made to throttle and control flow. System pressure placed under the disc in a globe valve (Figure 10-6-2) helps prevent erosion, or wire drawing, on the seating surface. Also, a globe valve tends to be linear through its travel from closed to fully open, and provides fine flow control.

The major disadvantage of a globe valve is flow restriction. It does not allow straight-through flow, as does a gate valve. Also, it is comparatively expensive.

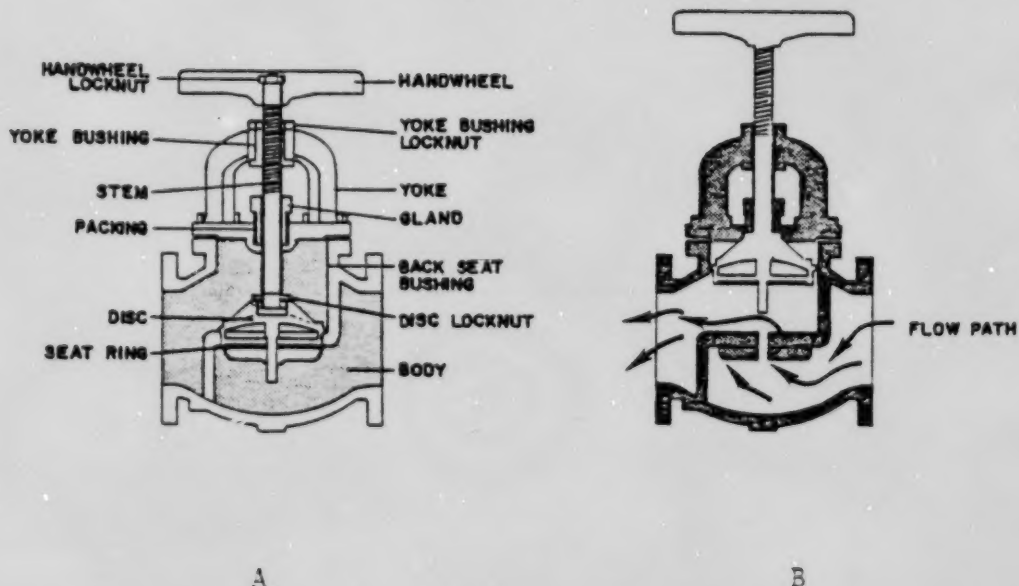


Figure 10-6-2. Globe valves, cutaway views showing (A) parts identification and (B) typical flow path.

Ball valves (Figure 10-6-3), the lowest costing of all valves, are widely used in the petroleum industry. Advantages, in addition to low cost, include its quick-opening feature. By turning a lever handle only 1/4 turn, the valve moves from closed to fully open. Also, no internal restrictions means full flow - just as with the gate valve - and no pressure drop. Unlike the gate valve, it cannot withstand high pressures and temperatures. In a power plant it may be found in some low-pressure, low-temperature water systems, but in general it is a petroleum industry valve.

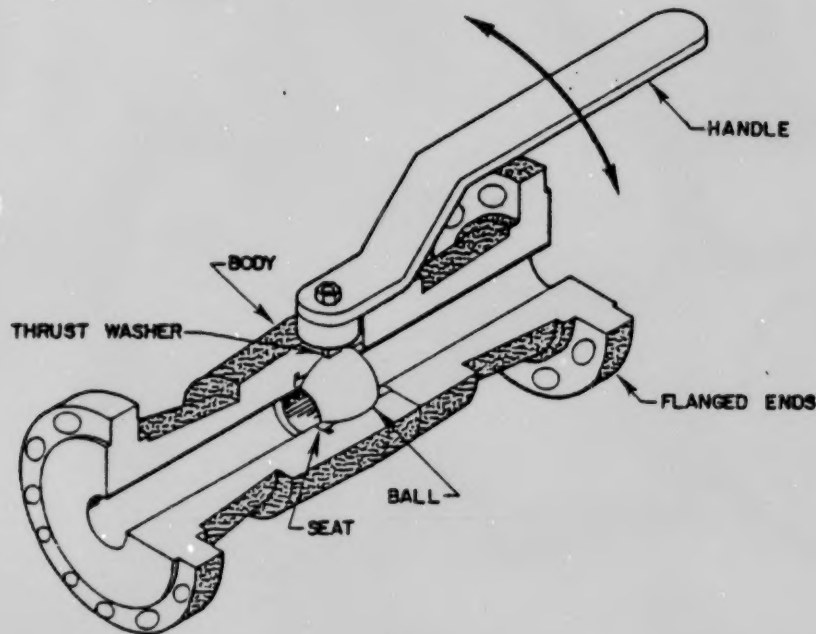


Figure 10-6-3. Ball valve, cutaway view.

Check valves (the name speaks for itself) prevent flow from reversing in a pipe (perhaps a better way to say it is that it permits flow in only one direction in a pipe). There are three basic types of check valves:

Swing.

Lift.

Ball.

A swing check valve (Figure 10-6-4) offers a fairly straight-through flow path with the least amount of obstruction. Turbulence and pressure drop across the valve measures low. This valve is the companion of the gate valve and can be installed in a horizontal or vertical pipe run; however, in a vertical run it must be installed so that the gravity pulls the disc down against the seat.

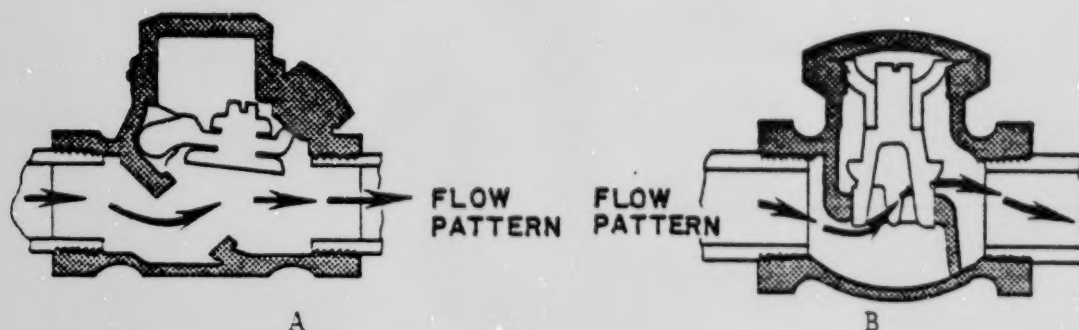


Figure 10-6-4. (A) Swing check valve, cutaway view; (B) horizontal lift check valve, cutaway view.

A lift check valve and a ball check valve have the same flow path as a globe check valve. Either is a companion check valve for a globe throttle valve. Some turbulence and pressure drop across such a valve is unavoidable. Also, this valve must be installed in a horizontal pipe run only.

(A special lift check valve can be installed in a vertical run.)

Plug valves relate to ball valves in the manner in which they operate: quick opening (1/4 turn) and straight-through flow (less turbulence). It offers some advantages over the ball valves, however, in that it is more compatible with water systems. It does not work well in high-temperature or high-pressure flows, but can hold its own in the lower ranges. Plug valves differ from the ball valves in that the disc and seat rings taper (Figure 10-6-5). Also, the trim can be renewed in some plug valves.

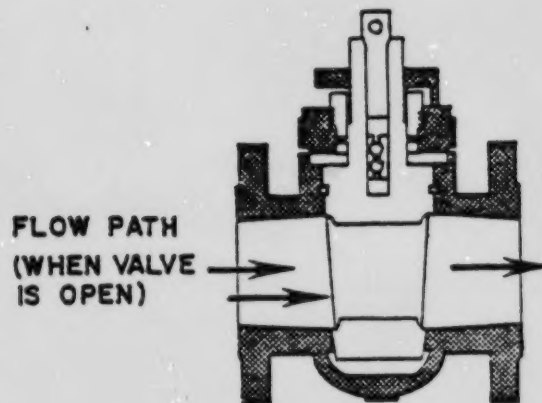


Figure 10-6-5. Plug valve in closed position.

Though not as widely used as gate and globe valves, plug valves can be found in power plants wherever lower pressure water systems are used.

Needle valves (Figure 10-6-6) may be described as "sophisticated globe valves. . ." Needle valves provide outstanding flow control. A restriction in the line, it "meters out" fine (small) quantities of the fluid from the

process stream. Expensive to manufacture, and limited to fine control, it can function in either high- or low-pressure systems, and finds application in chemistry labs, sample lines and other systems requiring precision metering and control.

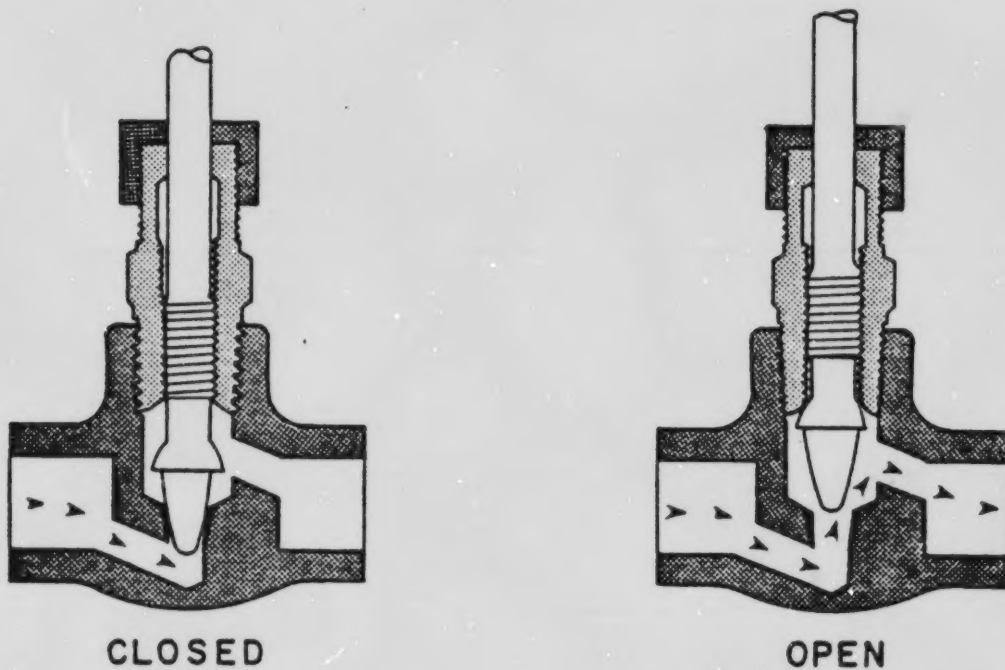


Figure 10-6-6. Needle valve; closed and open positions.

Diaphragm valves, with unique construction, allow no fluid in the process stream to come in contact with their stems or the valve bonnets. Diaphragm valves are thick (about 1/4 inch), and made of nylon corded neoprene (much like the sidewalls of automobile tires). The diaphragms fit between body and bonnet (Figure 10-6-7). When closed, the stem pushes the diaphragms into the valve opening, thereby inhibiting or stopping flow.

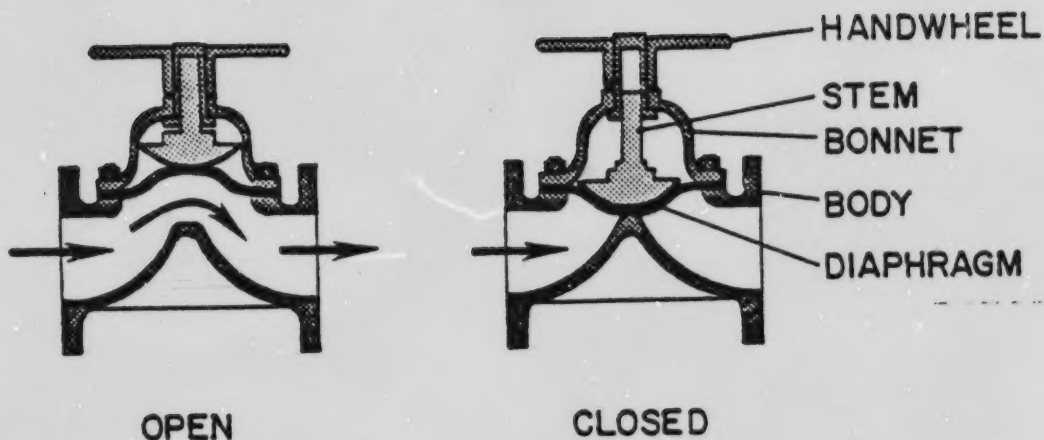


Figure 10-6-7. Diaphragm valve; closed and open positions.

Diaphragm valves are especially applicable in pressurized water reactors using boric acid. Because the acid never comes into contact with stem or the bonnet, boric acid leaks - the "nastiest" kind of liquid leaks - are eliminated.

On the other hand, diaphragm valves cannot be used in high-pressure or high-temperature lines. Also, it must be adjusted carefully so that the stem is not driven into the neoprene diaphragm. If cycled many times, the diaphragms tend to wear out or "fatigue," but when used and adjusted properly, it serves well in boric acid and other water/chemical systems.

Stop check valves (Figure 10-6-8) differ from the check valves (in function) only they have stems for opening and closing. When open, flow is allowed only in one direction; when closed, stop check valves perform like closed gate or globe valves. They save money in applications where both on-off and reverse flow prevention are needed. Normally used in

smaller lines (up to about 3 inches in diameter), stop check valves find application in a few power plant flow streams.

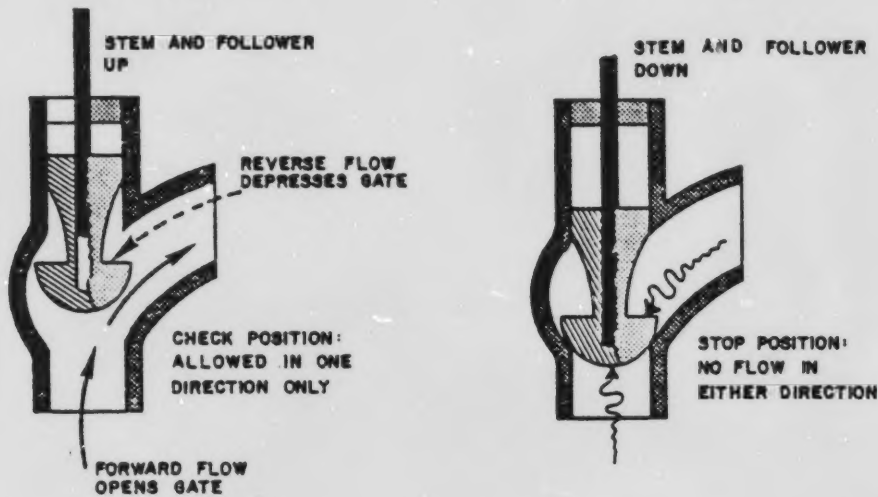


Figure 10-6-8. Stop check valve, showing stop position and check position.

Butterfly valves own a monopoly on the large (6 feet and larger) circulating water lines and others where vast quantities of fluid must be controlled. Butterfly valves, comparatively inexpensive, simple to manufacture, are nearly maintenance free. They do a fair job of throttling, but are not used for that purpose exclusively. On the other hand, butterfly valves leak a lot and, therefore, are not recommended for use in fluid process streams that require positive shut off; rather, it serves best in large diameter, low-pressure circuits where gate valve costs are intolerable while a little leakage is tolerable. The butterfly valve (Figure 10-6-9) uses a round disc seated against a neoprene seat.

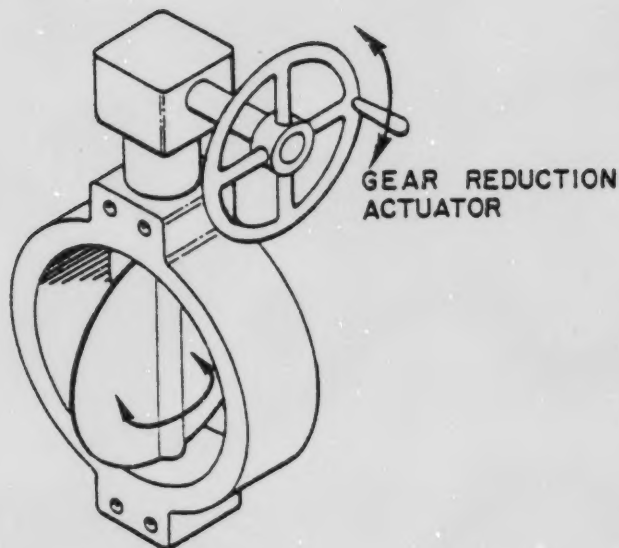


Figure 10-6-9. Butterfly valves, showing actuator and valve in open position.

Drag (cage trim) valves, newcomers in the field, do one thing: reduce noise.

Nuclear power plants, because of their design, dump steam to their condensers during startup, during trips (when turbine is not available to use the steam) and again at shutdown. When such a pressure drop (about 1000 psi) is taken across a gate or globe valve, the steam velocity created causes a deafening roar (a noise not unlike the exhaust roar from a jet aircraft engine). The drag valve (Figure 10-6-10), which uses a stack of etched plates (somewhat like phonograph records, except that the etches run radially from the center, and are not straight) made into a maze that causes "drag" across them. A plug, placed in the large center hole, is pulled out to expose more of the plates and

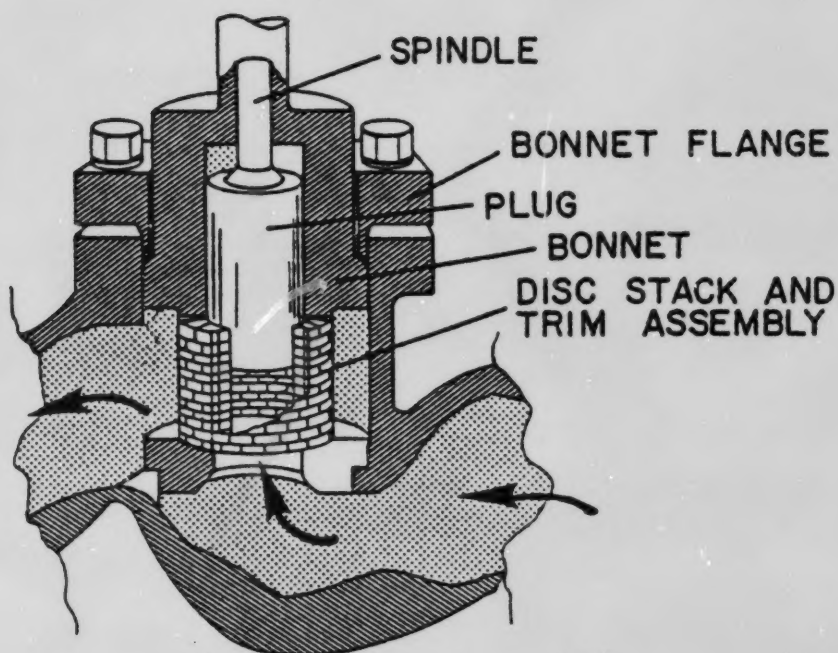


Figure 10-6-10. Drag valve, showing disc stack in place.

allow more steam to pass through the valve. Drag valves, usually larger and more expensive than ordinary control valves, present added leak paths, more chance of plugging, and premature wear of the multiple thin-walled plates. Even so, they have been finding more acceptance in recent years to combat noise pollution.

Angle valves are globe valves with their outlets turned 90° from their inlets. The internals on an angle valve, and the trim, differ not at all from those found in a globe valve. Angle valves are used in all the same applications as the globe valve. Often a throttle type valve is needed where the process flow makes a 90° turn, and an angle valve (Figure 10-6-11) can obviate the usual medley of

elbows and other fittings.



Figure 10-6-11. Angle valve, showing typical flow path.

Y-pattern globe valves, another variation of the "globe" design, combine the advantages of gate valves with globe valves. While the flow-through area of a Y valve is similar to that of a gate valve, the flow through can be throttled to any desired degree, same as in a globe valve. It is used wherever internal turbulence cannot be tolerated and is used extensively in nuclear power plants. Figure 10-6-12 shows a Y-pattern globe valve and its flow path.

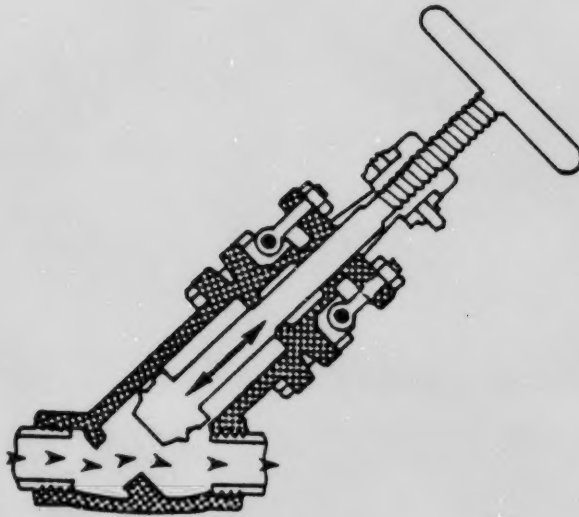
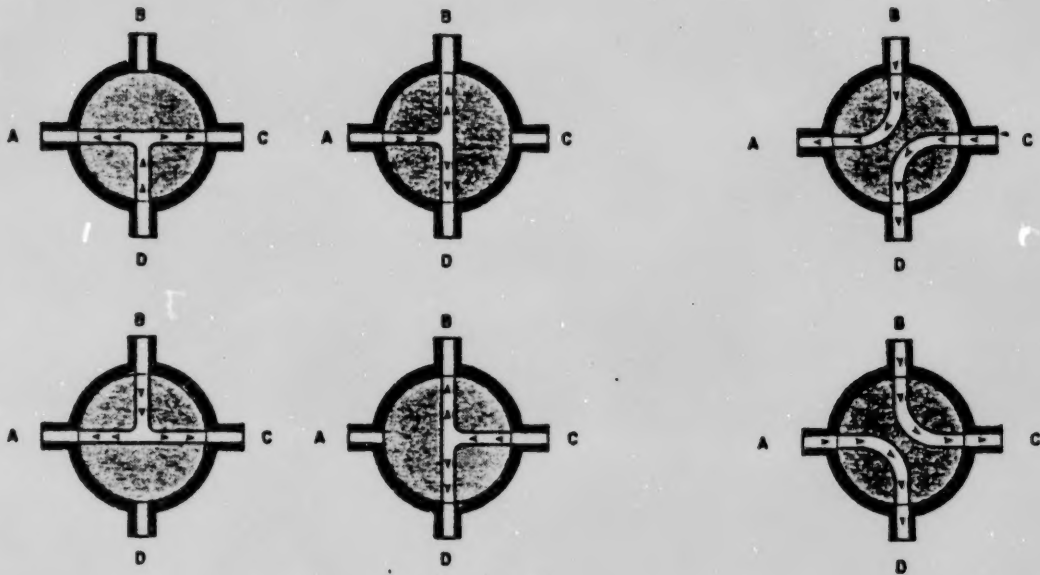


Figure 10-6-12. Y-pattern globe valve, showing typical flow path.

Three-way and 4-way valves (Figure 10-6-13) are variations from the ball or plug valve designs. Modified to include more ports as well as more inlets and outlets, these valves find favor where switching of fluids from one tank to another must be accomplished frequently. A good example is a power plant water treatment system, where routine switching from caustic or acid to a fresh water flush is required. These valves do not give many operating or maintenance problems.



Four possible lineups of
3-way valve.

Two possible lineups of
4-way valve.

Figure 10-6-13. Three-way and four-way valve flow patterns.

VALVE ACTUATORS

Valves open, close, check and meter only if mechanically actuated - something or someone must lift or lower the "gate." Many valves rely upon automatic controls; most, however, are activated manually.

MANUAL

In nuclear power plants manually operated valves outnumber all other dozens to one. The most familiar type is, of course, the round hand wheel. A variation is the reach rod, an extension of the stem with a hand wheel on the end. This arrangement appears in nuclear plants wherever a valve is situated in a high radiation area that has shielding around it: the valve stem is extended by a reach rod through the shielding for safe operation. Another manual-remote concept used extensively is the "chain operator" - a special wheel (bolted to the hand wheel) with a chain running through it. This arrangement appears extensively in power plants where valves are installed high over head and cannot otherwise be reached from floor level.

MOTOR DRIVE

The motor-driven valve actuator (Figure 10-6-14) finds a number of applications in nuclear or any power plant. It can be attached to various types of valves, but the three most common are:

- Gate valves.
- Globe valves.
- Butterfly valves.

But motor drives are expensive, so they are used with much forethought and consideration. For example, there are many applications in power plants where a valve should close because of abnormal conditions (low levels in certain tanks, high levels in shell side of feedwater heaters, and high levels in storage tanks). A level indicator relays a signal to the motor-drive and it closes or opens the valve. Motor-drives are also used on valves in start or

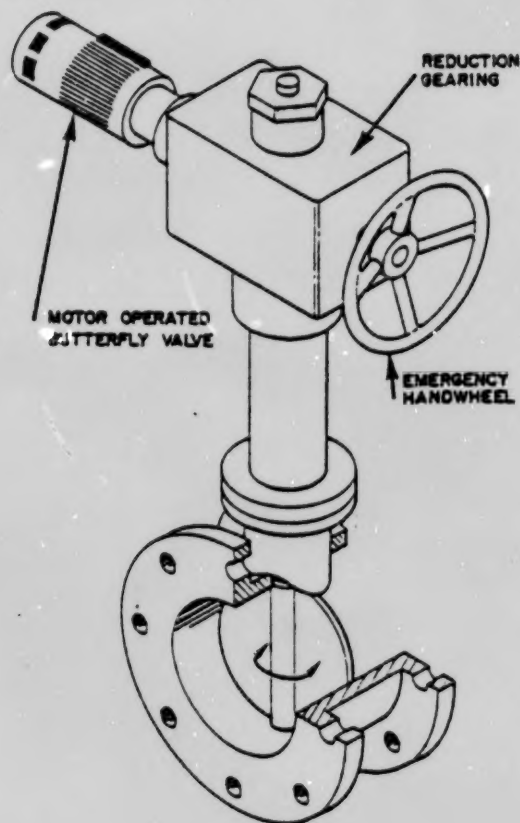


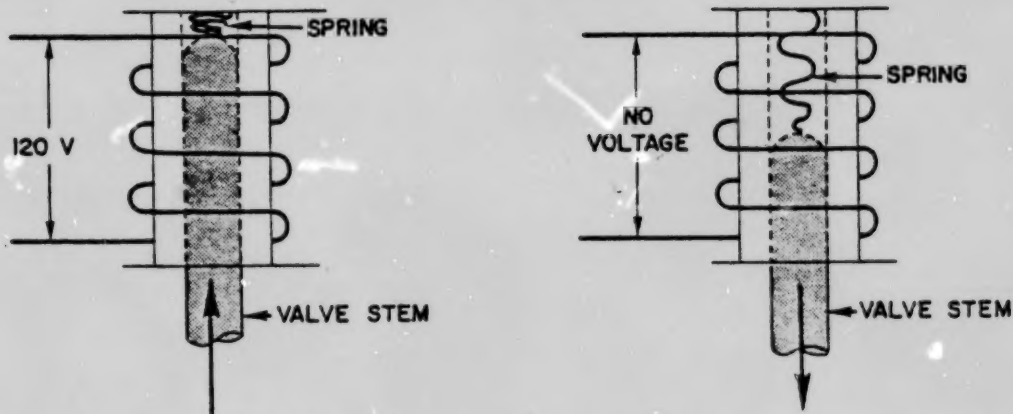
Figure 10-6-14. Motor-driven valve actuator.

stop applications where the control room operator cannot leave the station and must operate the valve from the control room.

Valve motor drives entail considerable expense because they incorporate sophisticated limit switches, torque switches and other costly hardware; even so, they are widely used in power plants.

SOLENOID

A solenoid actuator (Figure 10-6-15) usually can be



Solenoid energized. Magnetic force overcomes spring; valve stem is pulled up into solenoid. Valve open.

Solenoid de-energized. Spring forces valve stem down. Valve closed (electric failure-valve closes - fail-safe design).

Figure 10-6-15. Solenoid actuator operation.

associated with smaller valves. They are common in air systems, small fluid systems carrying water, oil or chemicals, but not in the larger main systems.

A solenoid is an electromagnet; thus, if the top part of a valve stem is made of magnetic iron or steel and placed so that it can be free to move in the center of the solenoid core, it will be pulled upward when the coil or solenoid is energized. If a spring is used to force it back down after the solenoid is de-energized, the valve then has both positive opening and closing capability.

As stated, solenoid valves are usually limited to

smaller instrument air lines, or small liquid fluid lines, such as sample lines, and limited in use to positive start and stop situations - they cannot be used to move a valve to any intermediate position.

PNEUMATIC

By a large margin, the pneumatic actuator (Figure 10-6-16) is the most common non-manual actuator found in

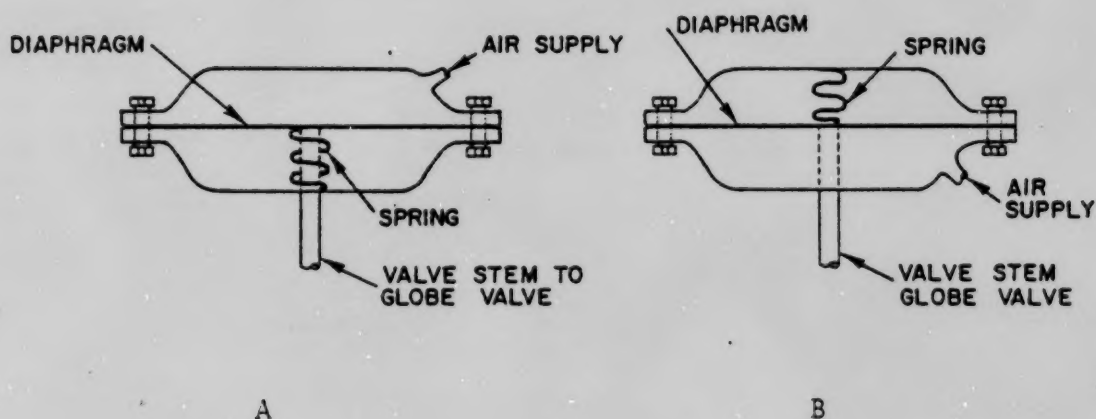


Figure 10-6-16. Pneumatic actuator: (A) No air above diaphragm allows spring to lift valve stem opening valve; this arrangement is called "air-to-close fail position open." (B) No air below diaphragm allows spring to lower stem, closing valve; this arrangement is called "air-to-open fail position closed." Some actuators employ air above and below diaphragm for a "fail-as-is" air loss condition.

a power plant. Because the air supply is easily controlled, the pneumatic actuator provides outstanding control for levels and pressures. Nearly every process flow stream has at least one such control valve. Easily identified, it rests atop the valve and has a large, round, semi-flat top. The vessel contains a diaphragm that increases its square inches of area for greater psi ratio.

HYDRAULIC

This actuator uses the well known, common and universal hydraulic cylinder. Generally used wherever one-quarter of a turn will fully open or fully close a valve (plug valves, ball valves and butterfly valves). Though not a common item in power plants, it is used wherever quick, positive response is essential.

VALVE APPLICATIONS

Two major considerations influence valve selection for any given application: 1) mechanical suitability and 2) safety.

MECHANICAL CONSIDERATIONS

Valves and the piping systems they control must be mechanically suited to their purpose. They must be properly sized, resistant to the materials they transport, capable of withstanding ambient temperatures and pressures, and designed

to be compatible with the flow process.

Size

Size need be considered here only in the context of the previous valve discussion; that is, valve size should be commensurate with pipe size, usually minimizing flow restriction except in those instances where flow-restriction is a designed function.

Materials

Materials, generally, conform to (NSSS and ASME) standards. The N-stamped valves used in NSSS circuits are almost always made of stainless steel. Valves used in petroleum product (gas, oil, diesel) lines may be made of brass or even more exotic metals. Bronze valves prevent sparking in hydrogen lines. But most valves utilize less expensive iron and steel components.

Pressure Ratings

Pressure ratings, identified as previously described (SP, WOG and so on), must be compatible with the materials transported. It should be noted that many iron-steel valves are rated as high as 1000 psia. But, in the high-pressure and/or high-temperature NSSS circuits of a nuclear power plant, stainless steel valves with rated packing are prevalent.

Service Requirements

Service requirements, a determinant of all the above factors (size, materials and pressure ratings), goes further. Both pressure and temperature can establish unique requirements, and both influence flow characteristics of a given material through a piping system. Also, fluid properties

(gas, liquid, liquid containing solids), fluid stability (phase changes, such as from water to steam) and corrosiveness influence valve selection, as noted, for example, in the choice of brass for petroleum products. Fluid friction may or may not be tolerable in certain flow systems; if not, the Y-pattern valve might be used in lieu of a standard globe valve. And, finally, each valve's intended function dictates selection from the various classifications of valves discussed early in this module: What must the valve do? Open, close, regulate, check or inhibit flow.

And, while all these mechanical considerations weigh heavily in valve selection, safety remains the primary consideration.

SAFETY CONSIDERATIONS

Safety maintains a paramount position in the design and operation of any nuclear power plant. Generally it is correlated with random radiation detection and prevention, but it must be scrupulously pursued in all areas of power plant operation. Thus, safety extends into valve selection as a primary determinant.

Safety "Class"

Safety "class" or classification may best be described by example. Consider the consequences of a valve failure in a condensate line; no immediate hazard to operators or facilities would ensue, certainly no radiation hazard potential would arise, and plant productivity would continue apace. On the other hand, a valve failure in a radioactive liquid system might create a highly hazardous condition, and likely could interrupt production. In any event, the

first failure is not in a "class" with the second. In the ASME specifications for valves (Section III), safety criteria for valve manufacture, testing and use falls into three categories - Class 1, 2 or 3. Thus all valves are classified for safety, but certain ones serve no other purpose except protection of the system and operators.

Safety Valves

Safety valves (Figure 10-6-17) used wherever compressible

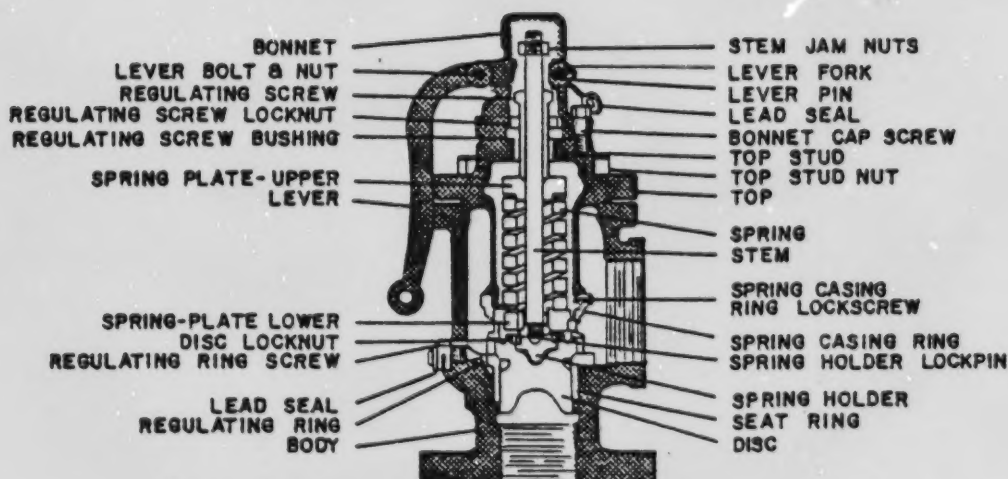


Figure 10-6-17. Safety valve.

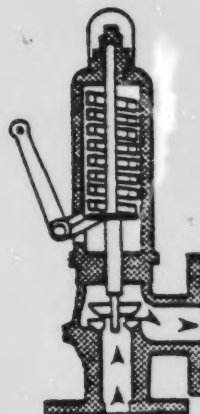
fluids such as steam or other gases are contained, release (or "pop off") whenever pressure exceeds a predetermined limit. Usually safety valves open fully when actuated and, therefore, relieve quickly, at full flow, until pressure drops to a predetermined low - called the "blowdown" pres-

sure - at which it closes.

Relief Valves

Relief valves (Figure 10-6-18), used in systems con-

Figure 10-6-18.
Relief valve,
showing typical flow path.



taining noncompressible fluids such as water or oil, also open (or "pop off") when pressure exceeds the predetermined limit. But, rather than "pop" fully open, it merely "simmers," or flutters between open and closed as necessary to offset the excess pressure.

"Code" Safety Requirements

"Code" safety requirements, Federal, state and local laws and regulatory codes, stipulate the limitations of safety valves and relief valves incorporated into a nuclear power plant's process streams. Similar codes apply to piping and pipe fittings as well.

PIPING

Piping may be described as any closed conduit of circular section and constant internal diameter. Nuclear power plant piping, because of its stringent specification, brought piping into a new era. Coal-fired plants caused the pipe industry to encompass a new term, "scheduling," and to instill new standards of schedules, or scheduled wall thickness. (Schedules are listed in *USAS B36.10 - 1959.) In general, schedule numbers reflect wall thickness, with high schedule numbers indicating thicker walls; however, pipe size is a factor, also. For example, in Table 10-6-1, a partial presentation of pipe diameters and wall thicknesses for various schedules, note that, under Schedule 40, a nominal 1 inch pipe has a wall thickness of 0.133 inch, while a nominal 4 inch pipe has a 0.237 inch wall thickness.

In any event, with the predominance of stainless steel pipe in nuclear power plant applications, scheduling has become a significant specification determinant. Also, pipe schedules provide the design engineer quick reference when selecting a pipe for a special job. In nuclear applications, pipe and valve selection within the code, lend great significance to the pipe schedules set down by USAS B36.10.

Again the codes must be emphasized so that their impact upon nuclear power plant construction can be fully appreciated: Nuclear power plants cannot be built until all the piping and valves meet the requirements of these codes.

* USA Standard for Steel and Wrought Iron Pipe.

TABLE 10-6-1

PIPE SCHEDULE AND RELATED DATA

Size		Wall Thickness	Nominal Weight/ft	Weight Class	Schedule No.	Test Pressure	
Nominal	Outside Dia					Grade I	Grade II
in.	in.	in.	lb			psi	psi
1/8	0.405	0.068	0.24	std	40	2500	2500
		0.095	0.31	XS	80	2500	2500
1/4	0.540	0.088	0.42	std	40	2500	2500
		0.119	0.54	XS	80	2500	2500
3/8	0.675	0.091	0.57	std	40	2500	2500
		0.126	0.74	XS	80	2500	2500
1/2	0.840	0.109	0.85	std	40	2500	2500
		0.147	1.09	XS	80	2500	2500
		0.294	1.71	XXS	...	2500	2500
3/4	1.050	0.113	1.13	std	40	2500	2500
		0.154	1.47	XS	80	2500	2500
		0.308	2.44	XXS	...	2500	2500
1	1.315	0.133	1.68	std	40	2500	2500
		0.154	1.47	XS	80	2500	2500
		0.308	2.44	XXS	...	2500	2500
1 1/4	1.660	0.140	2.27	std	40	2500	2500
		0.191	3.00	XS	80	2500	2500
		0.382	5.21	XXS	...	2500	2500
1 1/2	1.900	0.145	2.72	std	40	2500	2500
		0.200	3.63	XS	80	2500	2500
		0.400	6.41	XXS	...	2500	2500
2	2.375	0.154	3.65	std	40	2500	2300
		0.218	5.02	XS	80	2500	2500
		0.344	7.46	...	160	2500	2500
		0.436	9.03	XXS	...	2500	2500
2 1/2	2.875	0.203	5.79	std	40	2500	2500
		0.276	7.66	XS	80	2500	2500
		0.375	10.01	...	160	2500	2500
		0.552	13.70	XXS	...	2500	2500
3	3.500	0.216	7.58	std	40	2500	2200
		0.300	10.25	XS	80	2500	2500
		0.438	14.32	...	160	2500	2500
		0.600	18.58	XXS	...	2500	2500
3 1/2	4.000	0.226	9.11	std	40	2400	2000
		0.818	12.51	XS	80	2800	2800
4	4.500	0.237	10.79	std	40	2200	1900
		0.337	14.98	XS	80	2800	2700
		0.438	19.00	...	120	2800	2800
		0.531	22.51	...	160	2800	2800
		0.674	27.54	XXS	...	2800	2800
*							

* Pipe of larger sizes - information is available from USAS 336.10 - 1959 Standards.

Seamless pipes for nuclear power plant application call for some understanding of how seamless pipe is made. A large ingot of stainless steel is heated to white hot, then forced over a spinning mandrel of very hard material, causing the steel to be shaped into a pipe without a seam. It might be thought of as a special forging process, forcing the hot metal onto a forge tool (the spinning mandrel). The process is somewhat like forcing a wad of bubble gum over the end of one's finger - the end result is a piece of bubble gum that looks something like a piece of pipe.

While stainless steel pipe fulfills the industry's most stringent demands in most instances, other pipe materials meet some code requirements. Carbon steel pipes - the workhorse of the workaday industry - can carry water, steam, petroleum products and some chemicals. Because of its lower cost, it is used wherever the codes allow.

Chrome-moly pipe finds some application in nuclear power plants - it is quite compatible with hot liquid sodium, for example, and applicable in sodium cooled systems.

Brass and copper piping - usually in the form of small-diameter tubing - finds considerable application in low-pressure, limited flow circuits such as air lines for valves, instrumentation and the like. Also, it may be used extensively in domestic applications within a plant, such as water coolers, showers and toilet facilities.

PVC (polyvinyl chloride) piping may be used limitedly in domestic areas. Its greater application, however, is in handling strong acids and harsh caustics under low pressure and at modest temperature. PVC is exceptionally easy to use, requiring none of the usual complement of pipefitter tools, only a hacksaw and threader. A similar material, ABS, used for piping, finds little if any application in nuclear power plants.

Asbestos-concrete piping provides a comparatively inexpensive means of low-pressure, bulk water transportation. Typical installations might include:

Potable water main to power plant.

Cooling water mains to power plant.

Effluent discharge from plant.

Sewage discharge from plant.

A special variation of asbestos-concrete pipe with numerous small perforations in it may be installed below ground level around the perimeter of a plant to provide drainage.

PIPE FITTINGS

Piping includes pipes, valves and all the hardware needed to hold them together and in place. This hardware, called "pipe fittings," consists of many items, the most significant of which are described below.

WELDS

Welds, used to join pipe ends together - especially large-diameter pipe - and in numerous other applications, generally fall into one or the other of two categories: 1) butt welds and 2) socket welds. In a butt weld, two pipe ends of the same diameter are butted together and a weld seam is made as shown in (Figure 10-6-19). In a socket weld, the end of one pipe is flared (enlarged) to allow the end of another pipe to be inserted into it and then a weld seam is made at the end of the outside pipe.

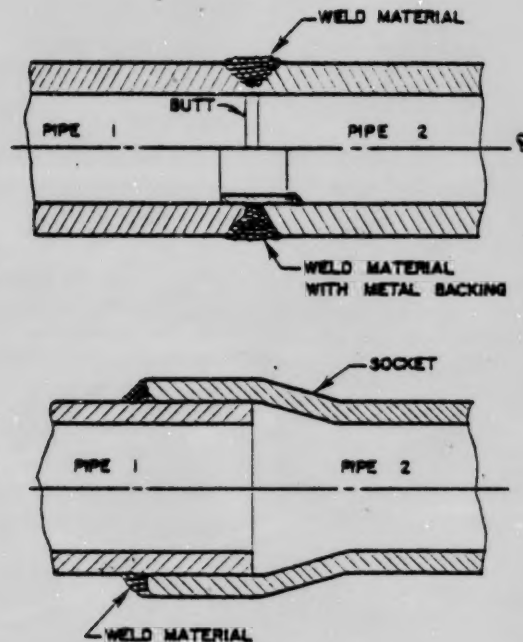


Figure 10-6-19. Pipes joined by butt weld (A) and by socket weld (B).

FLANGES

Flanges connect pipes to pipes (Figure 10-6-20), pipes to pump casings, pipes to valves, and so on. Generally, flanges are secured by bolts. Gaskets are used to provide firm seals, and spacers may be used to provide a tight union without pulling a pipe from its proper position or creating undue stress on any part of the circuit.

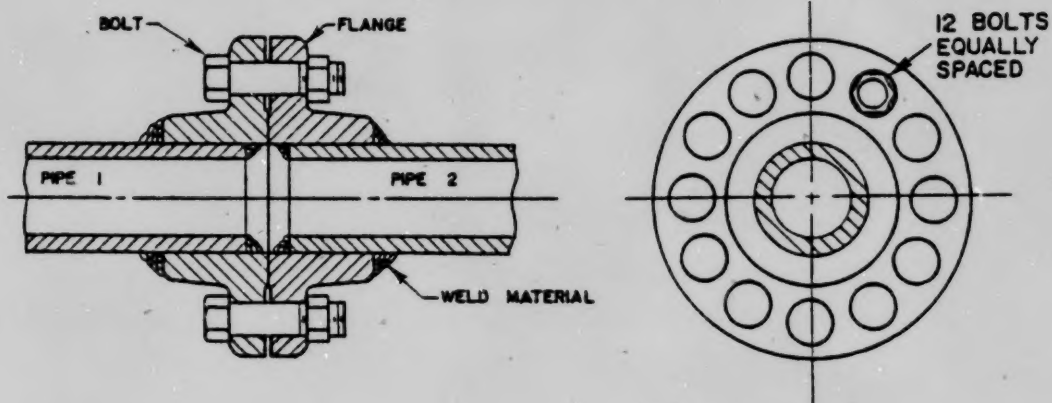


Figure 10-6-20. Bolted flange connection. (Note: Bolts encircle entire flange circumference.)

UNIONS

Unions provide another means of joining one pipe to another. Usually a union is a threaded sleeve, but it can be welded (Figure 10-6-21).

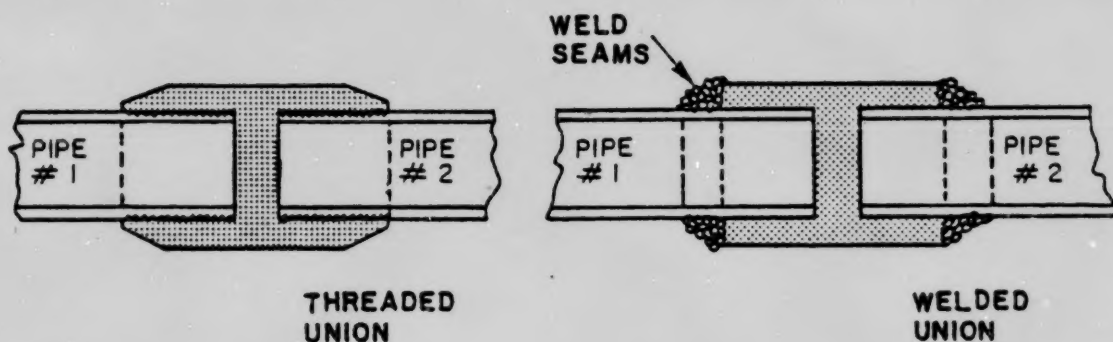


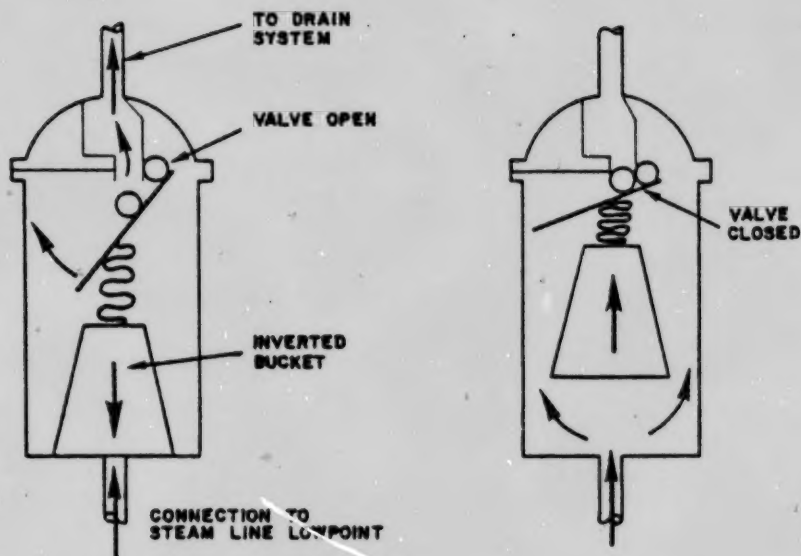
Figure 10-6-21. Union-connected pipes.

EXPANSION JOINTS

Expansion joints may be used on both the suction and discharge sides of a pump so that pipe expansion will not move the pump off its footing. (Long-length pipe runs, subject to varying temperatures, expand and contract measurably.) Expansion joints appear to be "wrinkles" or corrugations in the pipe.

STEAM AND WATER TRAPS

Steam and water traps collect condensation from steam systems. Large amounts of water condense inside the lines. This water can be damaging to equipment, especially turbine blades, if allowed to come into contact with it. Traps are usually installed in low points of a steam line - this is where the water tends to concentrate. Several trap designs are available; however, the most popular is the "inverted bucket" design (Figure 10-6-22).



"Bucket" sinks when filled with concentrate, causing valve to open, expelling condensate.

When steam can no longer enter "bucket," it sinks, opening outlet valve for condensate.

Figure 10-6-22. "Inverted bucket" condensate trap.

FILTERS AND STRAINERS

Filters and strainers are installed wherever pure flowing fluid is required, insofar as particulate matter is concerned. A good example, in a nuclear plant, would be the suction sides of pumps for radioactive laundry waste (to the waste treatment area). Laundries produce large amounts of line, which must not be allowed to get into the pumps.

FLOW ORIFICES

Flow orifices restrict flow in a line. For example, a very high pressure line that feeds a small tank might fill the tank too rapidly, so an orifice placed in the line

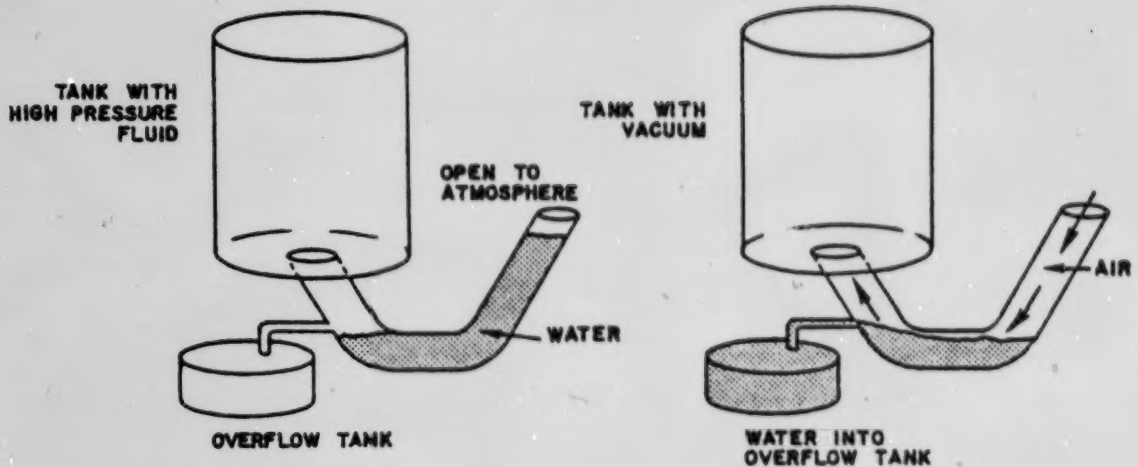
restricts the fill rate. Many applications of flow orifices can be found in power plants.

RUPTURE DISCS

Rupture discs, used instead of (or in conjunction with) relief valves, are metal plates that "blow out" at a predetermined pressure. These discs are used extensively in power plants.

VACUUM BREAKERS

Vacuum breakers are relief valves in reverse. Large tanks are generally designed to take several hundred pounds of internal pressure but usually cannot stand excessive external pressure (vacuum conditions); therefore, a vacuum breaker allows atmospheric conditions to enter a tank at some predetermined pressure (Figure 10-6-23).



Normal Condition:
High pressure inside tank.

Abnormal Condition:
Pressure inside tank reduced to vacuum; water in vacuum breaker pushed into overflow tank; outside air rushes into tank to increase pressure to atmosphere.

Figure 10-6-23. Vacuum breaker: operating scheme to relieve vacuum condition in tank.

PIPE HANGERS

Pipe hangers support pipes; pipes can, and do, get heavy, especially when filled with fluid. A long run of pipe must be supported, if above floor level. The "code" delineates hanger requirements - an operator should be familiar with them.

PIPE SNUBBERS

Pipe snubbers, closely related to pipe hangers, restrict

the movement of pipe due to expansion, turbulence and the like. Snubbers restrict, but do not stop, pipe movements by two methods: 1) by mechanical means and 2) by hydraulic means. Mechanical snubbers restrict by means of a large, heavy spring. Hydraulic snubbers use oil.



EXERCISES

1. Refer to symbols (Figure 10-6-24); answer the following questions as they relate to Figure 10-6-25:
 - a. What purpose do (1) and (1) serve?
 - b. Why are (1) and (1) gate valves?
 - c. What purposes do (2) and (2) serve?
 - d. What purposes do (3) and (3) serve?
 - e. What purposes do (4) and (4) serve?
 - f. What purposes do (5) and (5) serve?
 - g. What purpose does (6) serve?
 - h. Why is there a recirculation line from the discharge of the pumps back to the surge tank?
 - i. What other device could be used in this line instead of (6) ?
 - j. Why is (7) a globe valve? What purpose does it serve?
 - k. What purposes do (8) and (8) serve?
 - l. What purposes do (9) and (9) serve?
 - m. Which symbol appears most often in this system?
Is this realistic?
 - n. What purpose does (10) serve?

o. What purpose does (11) serve?

SYMBOL	DESCRIPTION	SYMBOL	DESCRIPTION
	GATE VALVE		DRAG VALVE
	GLOBE VALVE		BUTTERFLY VALVE
	CHECK VALVE		BALL VALVE
	PLUG VALVE		RELIEF OR SAFETY VALVE
	ANGLE VALVE		VACUUM BREAKER
	3-WAY VALVE		ORFICE
	4-WAY VALVE		DUAL STRAINER
	Y PATTERN GLOBE VALVE		EXPANSION JOINT
	NEEDLE VALVE		PNEUMATIC CONTROLLED GLOBE VALVE
	SAUNDERS DIAPHRAGM VALVE		CENTRIFUGAL PUMP
	STOP CHECK VALVE		ASME SECTION III "N" STAMP

Figure 10-6-24. ASME symbols for flow-control devices.

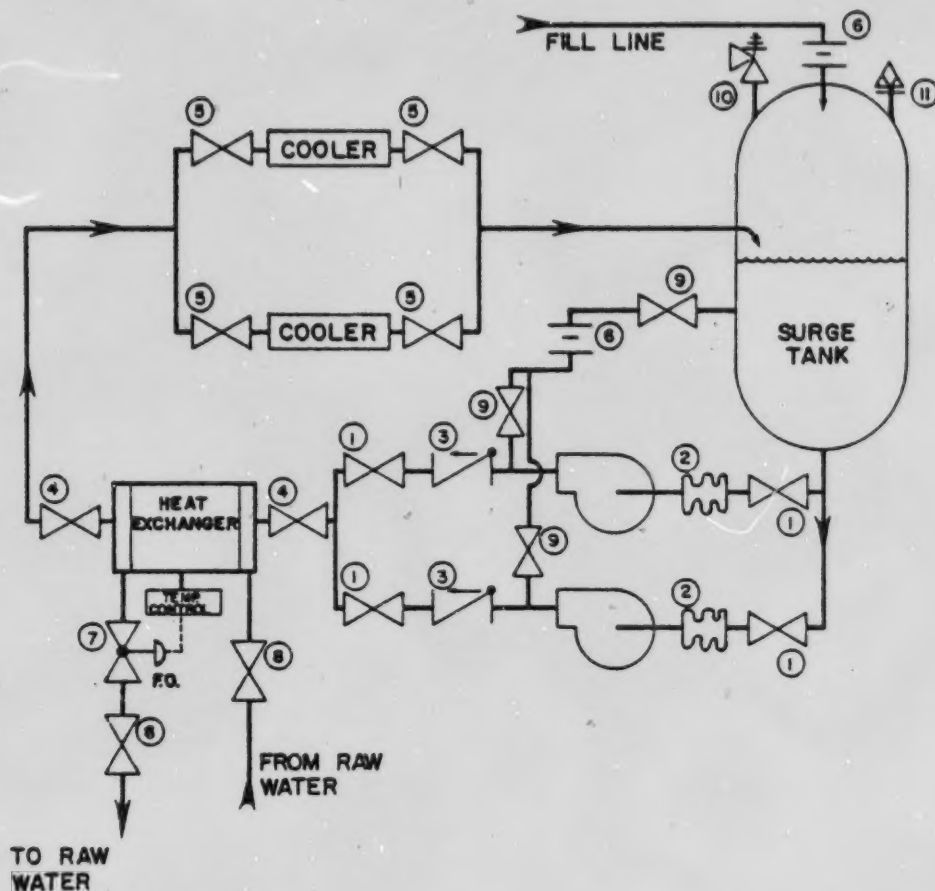


Figure 10-6-25. Hypothetical cooling system.

2. From information available in ASME "Boiler and Pressure Codes," Section III, write a 100-word report on what a valve manufacturer must do to earn an "N" stamp for a given valve.
3. From Table 10-6-1, find wall thicknesses, inside diameters (ID) and weight/ft for the following:
Schedule 40, 2 inch nominal.

Schedule 160, 2 inch nominal.
Schedule 80, 4 inch nominal.
Schedule 160, 4 inch nominal.
Schedule 40, 3/4 inch nominal.
Schedule 80, 3/4 inch nominal.



MATERIALS

Gate valve.
Globe valve..
Plug valve.
Butterfly valve.
Check valve.
Y-pattern globe valve.
Diaphragm valve.
ASME "Boiler and Pressure Code," Section III.
Approximately 30 feet of 1-inch pipe.
4 1-inch ells.
2 1-inch flanges.
1 1-inch flow meter.
2 manometers.
1 1-inch pump.
Appropriate reservoir.
Valve supplier's catalog and price sheet(s).
1 3-way valve.
1 4-way valve.
1 motor (or pneumatic) actuated valve.



PROCEDURES

1. Disassemble one each:

Gate valve.

Globe valve.

Check valve.

Identify all parts (refer to Figures 10-6-1, 10-6-2 and 10-6-3): reassemble (in working order) each valve.

Also, answer the following questions about each valve:

What kind of inside trim is used?

Are seats renewable?

What do letters and numbers (if any) on body castings signify?

2. By using appropriate pipe, pipe fittings, pump, valve(s) and meters, assemble a simple piping loop similar to that shown in (Figure 10-6-26). Then, in succession, install one each of the following valve types in Position A and measure pressure drops at various throttle openings:

Gate valve.

Globe valve.

Plug valve.

Butterfly valve.

Check valve.

Y-pattern globe valve.

Diaphragm valve.

Record flow rates and drops on Data Table 10-6-1.

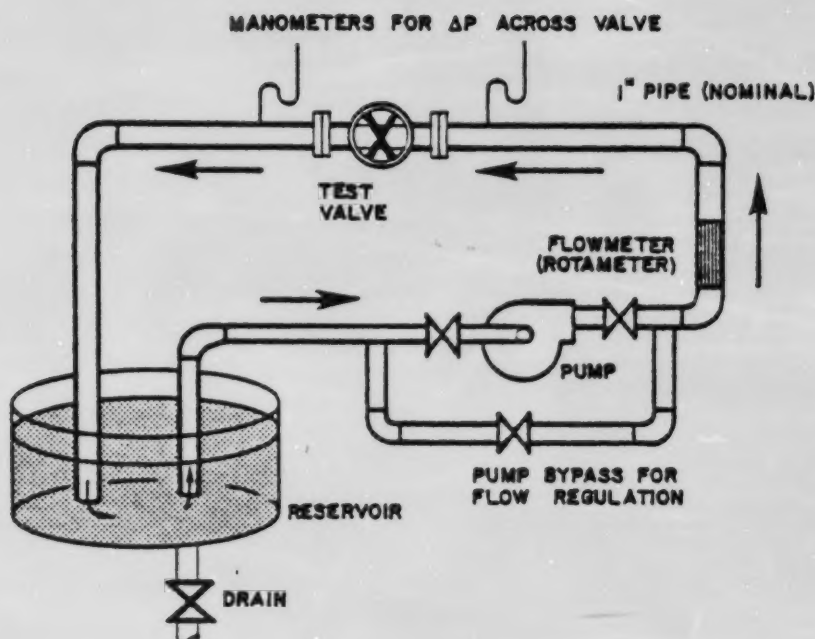


Figure 10-6-26. Typical hydraulic piping loop.

From Data Table 10-6-1, answer the following questions:

Which valve shows the greatest pressure drop?

Which valve shows the lowest pressure drop?

Which valve allows the greatest flow-rate/
opening?

3. From a supplier's catalog (provided by instructor), determine cost of each valve used in Procedure 2; list valves according to cost, in descending order.
4. Follow instructor's demonstration of a 3-way valve; list three everyday uses of this type valve.
5. Follow instructor's demonstration of a 4-way valve; list two everyday uses of this type of valve.

6. Follow instructor's demonstration of a motor (or pneumatic) activated control valve; plot valve position setting versus flow rate. Compare results with data from Data Table 10-6-1.



DATA TABLE

DATA TABLE 10-6-1

	Flow Rate	Pressure Drop, In. $\frac{1}{2}$ Hg						
		Gate	Globe	Plug	B'fly	Check	Y	D'ph'm
Full open								
3/4 open								
1/2 open								
1/4 open								



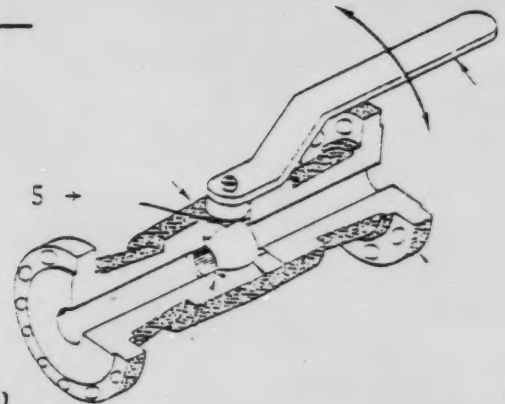
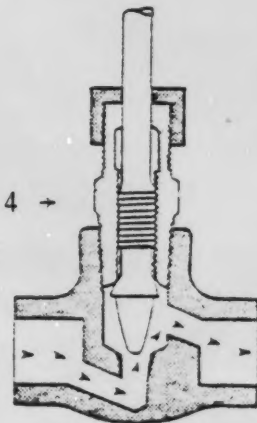
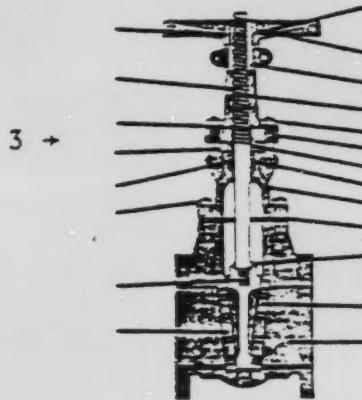
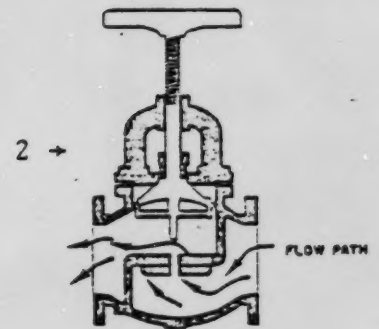
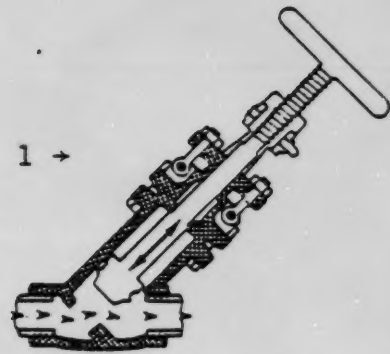
REFERENCE MATERIALS

The Crane Co. Flow of Fluids Through Valves, Fittings and Pipe, technical paper no. 410. Chicago: Crane Co.

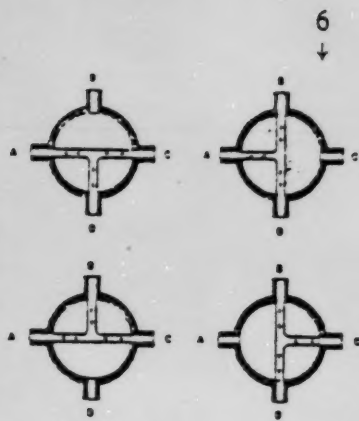


1. List the four major components of any valve:
2. Briefly describe each of the six classifications of valves (as discussed in this module):
3. Identify the two basic items of valve care and maintenance described in this module:
4. Thirteen kinds of valves, described generically in this module, are shown below; match valve number with name:

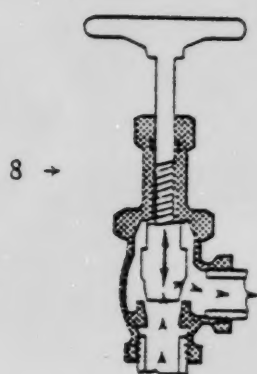
- a. Gate valves _____.
- b. Globe valves _____.
- c. Ball valves _____.
- d. Check valves _____.
- e. Plug valves _____.
- f. Needle valves _____.
- g. Diaphragm valves _____.
- h. Stop check valves _____.
- i. Butterfly valves _____.
- j. Drag valves _____.
- k. Angle valves _____.
- l. Y-pattern globe valves _____.
- m. Three-way and 4-way valve flow patterns _____.



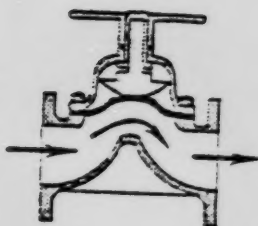
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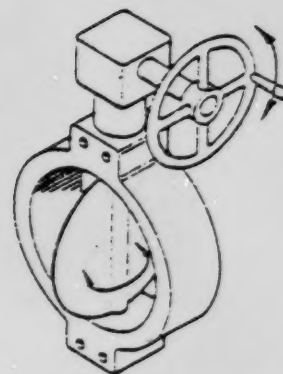
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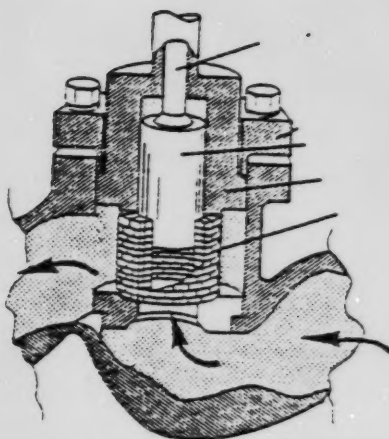
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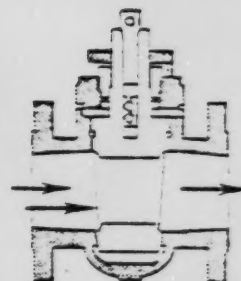
11 →



12 →



15 →



5. Name the five methods of valve actuation discussed in this module:

6. List the two major considerations influencing valve selection for any given application within a nuclear power plant:

7. Define (in 25 words or less) the phrase, safety "class" or classification.

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8. Write a brief description of the function of each of the following:

Safety valve.

Relief valve.

9. Based on information from this module, write a one-sentence definition for "piping."

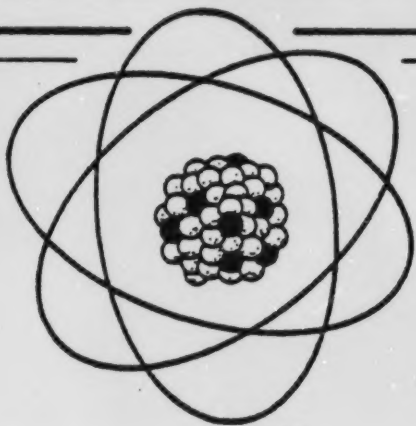
10. A pipe's "schedule" indicates what?

11. Generally, only one kind of pipe qualifies for NSSS applications. Of what material is it made?

12. List at least four pipe materials, other than those given in question 11 above, that are used in nuclear power plant piping:

13. The ends of two pipes of the same diameter may be joined together in various ways; list and sketch three:

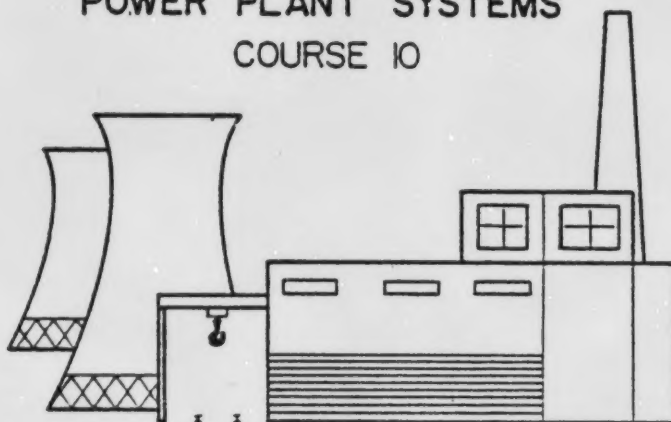
14. List at least six other devices used in or on a piping system that come under the general heading of "pipe fittings:"



NUCLEAR TECHNOLOGY

MODULE 10-7 ELECTRICAL TRANSMISSION AND DISTRIBUTION
SYSTEMS

POWER PLANT SYSTEMS
COURSE 10



TEC -SW

TECHNICAL EDUCATION RESEARCH CENTER — SOUTHWEST
4201 LAKE SHORE DRIVE WACO, TEXAS



COURSE MODULES

COURSE 10 POWER PLANT SYSTEMS

MODULE 10-1	Power Plant Fundamentals
MODULE 10-2	Power Plant Thermal Cycles
MODULE 10-3	Turbines and Generators
MODULE 10-4	Heat Exchangers and Condensers
MODULE 10-5	Pumps
MODULE 10-6	Valves and Piping
MODULE 10-7	Electrical Transmission and Distribution Systems
MODULE 10-8	Power Plant Fundamentals (Fossil-Fuel Energy Efficiency)
MODULE 10-9	Fossil Plant: Auxiliary Discussions

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Technical Education Research Center
Southwest
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Waco, Texas 76710



INTRODUCTION

Even though the power plant operator or technician may never extend his services beyond the confines of the main plant, his responsibility is subjected to no such restraint. His performance has far-reaching influence, throughout the system his plant serves, into every home, farm and factory on its grid. And, in fact, it affects other power plants - even other power companies - within the system network.

For these compelling reasons, an operator or technician should be aware of the entire system, understanding its overall makeup, and exercising a working familiarity with its major components.

This module covers the electrical system from generator output to consumer, describing not only the mechanics of transmission and distribution but also the machinery required to transmit and distribute electrical energy efficiently and without interruption.



MODULE PREREQUISITES

Student should have basic knowledge of electricity and should have completed Module 10-1, "Power Plant Fundamentals."



OBJECTIVES

Upon completion of this module, the student should be able to:

1. Identify all inplant currents (by voltage rating) found in an electric power generating plant.
2. Describe the physical and electrical attributes of the main transformer.
3. Identify the main components of a switchyard, and describe the function of each.
4. List and describe, in general terms, the instruments found in a control room that relate to plant functions pertaining to power transmission and distribution.
5. List, identify by function and power factors, and describe the components of a power transmission system, a system network, a primary network, a secondary network, and coordinated protective devices.
6. List safety hazards, and identify precautions and protective equipment and clothing associated with power transmission and distribution.



SUBJECT MATTER

Power plant generators produce almost all of the electricity used by industries, on farms and in homes. But generation is only a part of the process of supplying electrical power. The electricity must be transmitted from the plant to the users' geographical area then distributed to customers. (Figure 10-7-1).

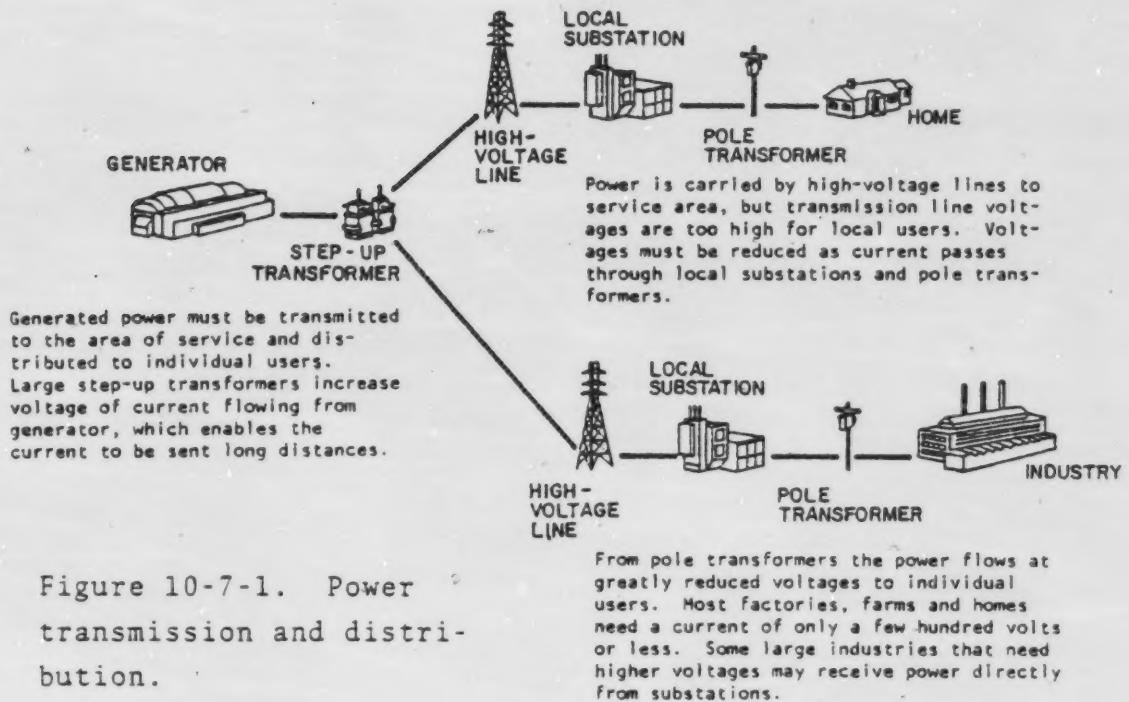


Figure 10-7-1. Power transmission and distribution.

Most electric power companies operate a number of generating stations positioned at planned locations throughout a particular region. The transmission lines of one station are, as a rule, connected in a network with the power company's other generating stations. Should one station experience an unexpected demand for additional electric power, the interconnect capability permits power transfer between stations to meet such demands. The network system enables power routing by way of a different transmission line if a particular line is out of order.

The transmission systems of many electric companies may join together in a grid. Such grids provide pools, or reserves, of electric power. Additionally, each power system usually maintains spare generators to supply power when needed. By use of the network system and the spare generators, no area should be without electricity in the event a single power station experiences a failure.

Personnel responsible for delivering power throughout the transmission system are called control room operators, or load dispatchers. From experience, they know approximately how much power is needed from hour to hour.

CONTROL ROOM

The "command post" of any power plant is its BTG (boiler-turbine-generator) board. It houses system gages, indicators, readout, and automatic recording charts.

The gages indicate various electrical data (amperes, volts, megawatts) as well as steam temperatures, combustion rates, gas pressures and water pressures and temperatures.

Colored indicator lights (red, green, white or yellow) signal conditions within key portions of the system.

Readout panels, consisting of one or two key words, flash on to alert control operators of conditions requiring immediate attention.

Recording graphs, positioned on both the front and back of the control board, automatically transcribe readings that make up a portion of the historical record of the plant. (To supplement these automated recordings, control operators manually record certain instrument recordings at specified time intervals.)

The control room is manned continuously by trained operators.

VOLTAGES

At the switching station, voltage is stepped down for transmission to local substations and is stepped down again before passing through secondary mains to customer's premises.

Table 10-7-1 lists typical transmission and distribution system voltages.

TABLE 10-7-1
TYPICAL VOLTAGES IN USE

Main Transmission	Sub Transmission	Primary Distribution	Secondary Distribution
69,000 V	13,000 V	2,400 V	120 V
*138,000 V	23,000 V	4,160 V	*120/240 V
*220,000 V	*34,500 V	*13,800 V	240 V
330,000 V	*69,000 V		480 V

* More commonly used.

If a power station generates 20,000 volts (Figure 10-7-2), which is raised to 138,000 volts for transmission, it must be carried over 138,000-volt (138 kV) transmission lines to switching stations situated in key load areas of the system. At the switching station, power is stepped down to 69,000 volts (69 kV) for transmission to local substations. (In some instances, power may be stepped down to 913.8 kV for distribution to commercial and industrial customers in local areas.)

Distribution transformers, positioned at the top of poles in residential areas, reduce voltage power to household levels (120/240 volts).

Substations reduce incoming voltage for local distribution. Each substation feeds its local load area by way of primary distribution feeders. Some substations operate at 2400 volts and others at 4160 volts and 13,800 volts. Generally, primary feeders run from one to five miles in length. In rural sections, where demands for electricity are not so demanding, feeders are sometimes as long as 10 to 12 miles.

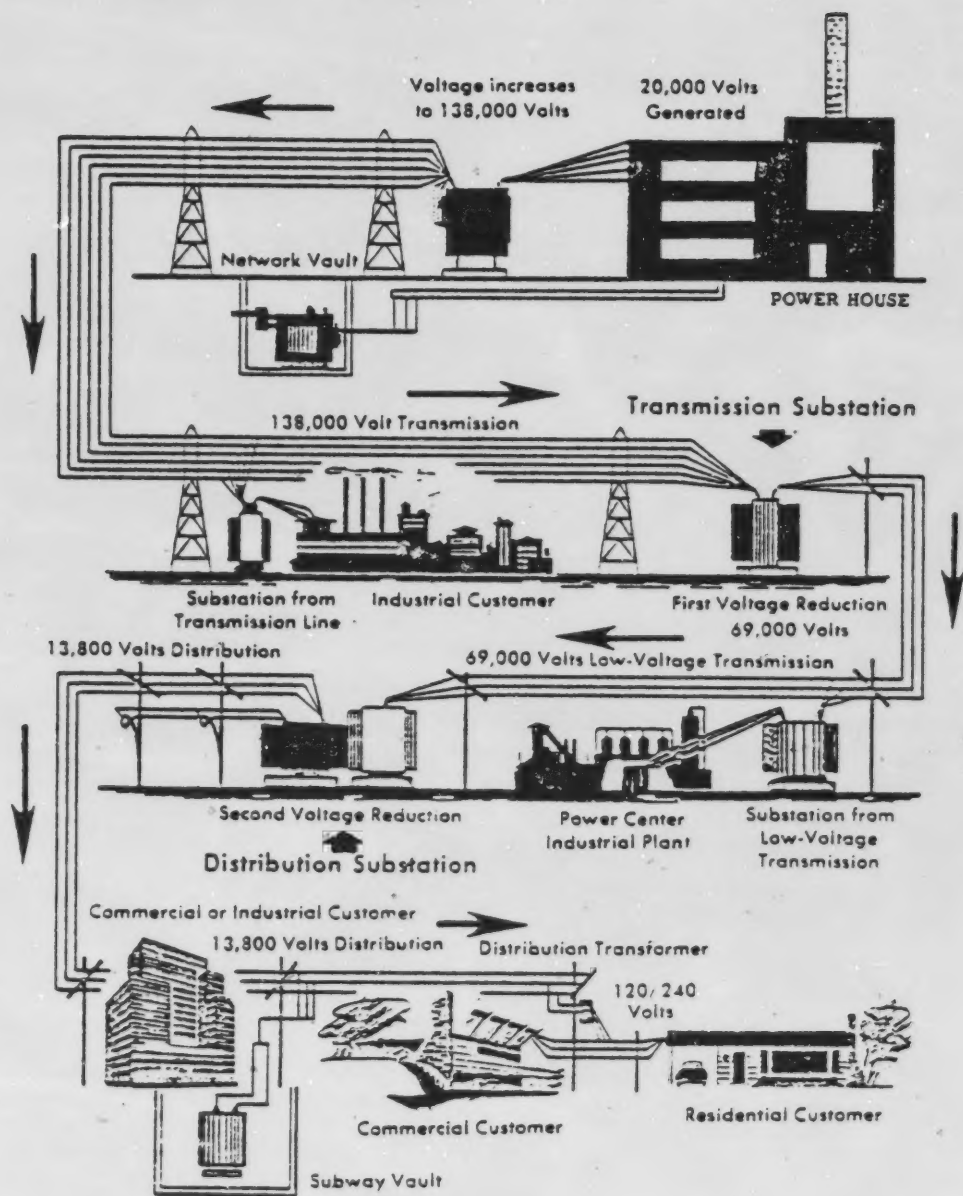


Figure 10-7-2.[®] Electric service, from generator to consumer.

Distribution transformers are connected to primary distribution lines. These transformers step primary voltage down from 2,400 volts (or 4,160 volts, or 13,800 volts) to approximately 120 volts (or 240 volts) for distribution to customers. Lines that carry electricity at utilization voltages (from the transformer to a customer) are called secondary distribution mains, and may be either overhead or underground lines. (Note: Secondary mains are not required for supplying large customers, such as railroads, large stores, or factories. In such instances, service wires or cables are connected directly to distribution transformers).

TRANSFORMERS

A transformer consists of two or more windings (a primary winding and one or more secondary windings) placed on a common iron core. (Figure 10-7-3). The winding connected to a power source is called primary, and the winding(s) connected to electrical load(s) secondary.

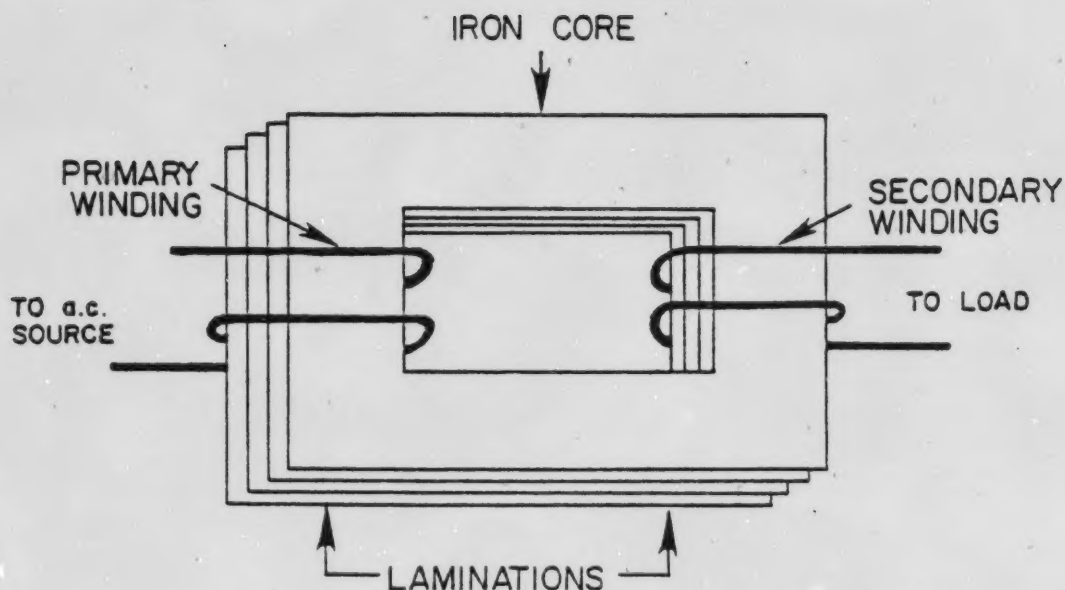


Figure 10-7-3. Simple transformer.

MAIN TRANSFORMER

At the main power plant, generated power (electricity) voltage is stepped up to its transmission value by a main transformer (Figure 10-7-4).

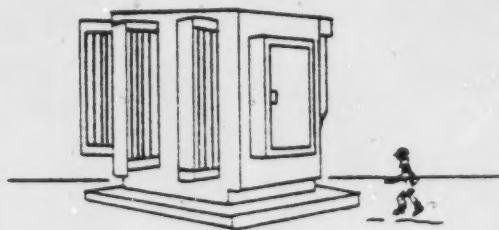


Figure 10-7-4.
Main transformer.

Electricity can be more efficiently transported at high voltages (less resistance), and ultra-high voltage (740 kV) transmission lines are becoming more common.

Other transformers may be used within a main plant to provide plant power needs (lights, motors, etc.).

DISTRIBUTION TRANSFORMERS

Distribution transformers, used in primary and secondary circuits, step down voltages. From primary mains to secondary mains, generally the step down is from 2400 volts (or 4160 volts, or 13,800 volts) to 120 (or 240) volts.

Most distribution transformers consist of a closed loop magnetic core (upon which are wound two or more separate copper coils), a tank (in which the core-coil assembly is immersed in cooling and insulating oil) and bushings for safe passage of leads through the cover.

DISTRIBUTION SYSTEMS

An electric distribution system is all the parts of an electric power system between the bulk power source and the consumer:

- Subtransmission circuits.
- Distribution substations.
- Distribution or primary feeders.
- Distribution transformers.

Secondary circuits.

Consumer services.

SUBTRANSMISSION CIRCUITS

Subtransmission circuits, which extend from the bulk power source to the various distribution substations, generally consist of underground cable, aerial cable, or overhead, open-wire conductors carried on poles.

SUBSTATIONS (SWITCHYARDS)

Substations function as sources of electrical energy supply for the local areas of distribution in which they are located. They receive energy transmitted at high voltage from the generating stations, then reduce voltages to values appropriate for local use. Substations usually house one or more power-transformer banks together with the necessary voltage regulating equipment, buses, and switchgear.

SUBSTATION EQUIPMENT

A typical substation might include:

Transformers - Used to step voltage down for distribution, or up for further transmission.

Voltage Regulators - Used to automatically adjust the ratio of electricity being transformed to bring voltage back to some predetermined value.

Air-Break Switches - Usually installed on both sides of a piece of equipment to effectively de-energize the equipment for maintenance.

Circuit Breakers - Either air or oil, designed to safely interrupt circuits while current is flowing. Contacts are usually made and broken under oil. Blasts of compressed air can also be used to quench the arc which forms.

Lightning Arresters - Used to discharge lightning voltage to ground.

ELECTRIC SYSTEM PROTECTION

The nature of electric phenomena is such that trouble may develop and cause considerable damage to equipment. Protection is mainly against sustained overloads, high temperatures, and internal faults. Sustained overloads and high temperatures related to generators and transformers usually can be taken care of by the control room operator, aided by instruments indicating magnitude(s) malfunction(s). Audible or visual signals, energized by automatic relays, are employed to warn of abnormalities when a predetermined value is exceeded. When internal faults develop, equipment is quickly (automatically) disconnected. Internal faults include short circuits, open circuits, or grounds.

A protection system should satisfy the following points:

Selectivity - The system should be able to distinguish which portion of a sectionalized system is not operating normally and disconnect only

that section, leaving the remainder of the system to function without interruption.

Perception - The protection system should distinguish between normal and abnormal conditions with extreme accuracy.

Sensitivity - The protection system should not allow any undue enlargement of the problem before protective actions are completed.

Safety is a paramount factor throughout the transmission cycle of electric power. In addition to internal faults, the utility company must consider many safety factors involving the entire system. The National Electric Safety Code, in addition to other accepted safety guidelines, enables utility companies to deliver electric power in the safest possible manner. In many instances, cities and towns enforce their own power delivery standards. Constant safety of the public as well as all employees is a paramount responsibility of utility companies.

OVERHEAD TRANSMISSION LINE SUPPORT

Power sent from a generating station to delivery points is transmitted over transmission lines strung on wood, concrete or steel poles and structures.

Steel towers are usually used for transmission lines with wood and concrete poles used for distribution circuits, but this distinction does not always hold true. The choice of support depends on terrain

to be crossed, conductor size, equipment to be carried, and other factors.

The most commonly used form of overhead transmission line construction consists of wooden poles with conductor wires attached to insulators mounted on wooden crossarms. Cedar and pine poles are most widely used poles in this country because of availability and economy.

Utility companies must overcome obstacles of trees, railroads, rivers, hills, weather and even pedestrians when constructing overhead lines (Figure 10-7-5).

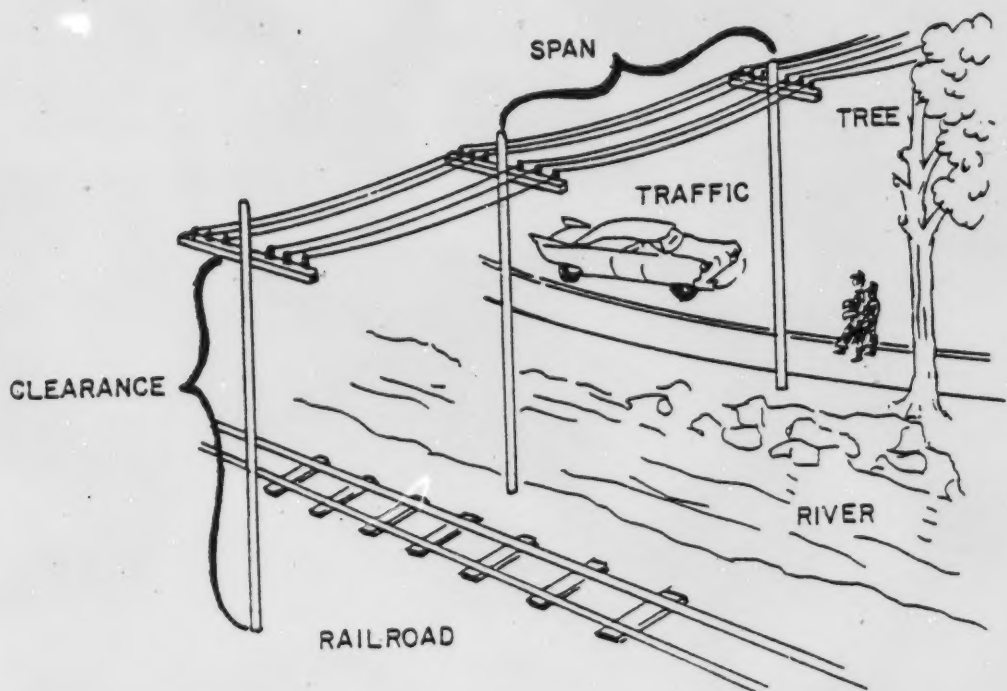


Figure 10-7-5. Various obstacles to power line construction.

INSTRUMENTATION

Instruments used in power transmission include recorders, indicators and integrators.

Recording instruments record wattage, voltage, frequency, amperage and power factors. Also, a totalizing wattmeter is used in many plants to sum generated kilowatts. Recording voltmeters and wattmeters are in common use to maintain continuous records of the plant voltage and kilowatt output. Other instruments record temperatures (e.g., transformer oil temperatures, generator-stator-coil temperatures, and generator-field-coil temperatures).

Indicating instruments include ammeters and voltmeters. Ammeters measure the magnitude of electrical current; voltmeters measure the value of electrical potential. Other indicating instruments include frequency indicators, power-factor meters, and synchronism meters. Also, kvar meters are used to measure reactive kilovolt-amperes.

Integrating devices include watthour meters and kvar meters. These integrating instruments can be operated singly, or they may be electrically added together to give a total reading. Gages are used to indicate oil pressure, air pressure, and other pressures. Other indicating instruments serve as recording devices while indicating pressure readings, vacuum readings, and so on.

LAMP FLICKER

Lamp flicker is the deviation from uniform light intensity when illumination momentarily dims. In the early days of electrical transmission, a wide range of voltage variation was permissible because consumers at that time were not accustomed to uniform lighting intensity and appliances and electrical devices were less sensitive to voltage variations. Today's consumers are more aware of steady voltage regulation, and repeated observations have shown that rapid changes of voltage are annoying and destructive to sensitive devices.

Voltage swings causing flicker are more frequent in industrial plants where starting heavy equipment causes abrupt voltage dips. Voltage regulation has been - and continues to be - one of the most difficult problems of the electrical energy supply.



EXERCISES

None.

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MATERIALS

None.



PROCEDURES

None



DATA TABLE

None.



REFERENCE MATERIALS

- Lish, Kenneth C. Nuclear Power Plant Systems and Equipment.
New York: Industrial Press, 1972.
- Nicholson, Paul W. Nuclear Electronics. New York: Wiley,
1974.

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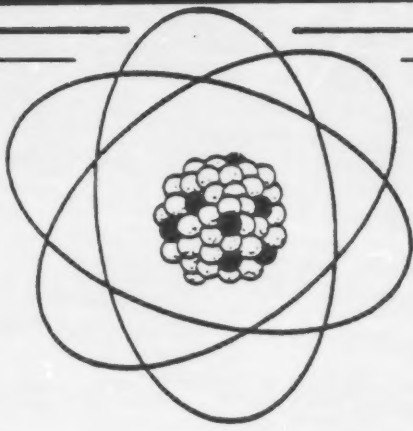
Visit a control center and a substation; answer the following questions:

1. Sketch and briefly describe a control center and a substation; for each, give purpose, physical size, safety devices and number of employees.

2. Briefly explain how frequency and voltage are controlled; indicate normal variations.

3. Briefly describe transmission lines, poles (or towers) and wires leading to and from substation.

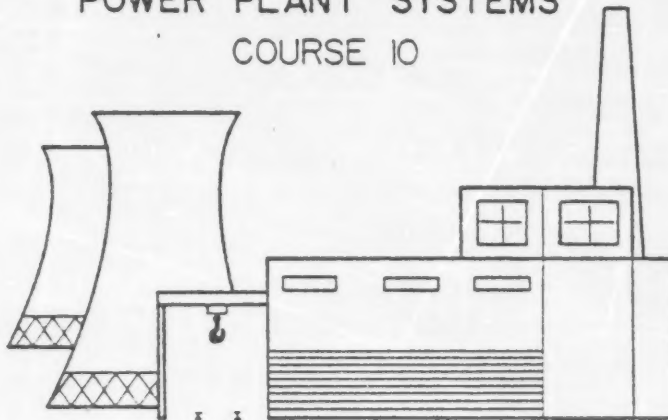
4. Briefly describe transformer(s) in substation; how many are there? What are their in and out voltages? What protective devices are employed?



NUCLEAR TECHNOLOGY

MODULE 10-8 POWER PLANT FUNDAMENTALS (FOSSIL-FUEL
ENERGY EFFICIENCY)

POWER PLANT SYSTEMS
COURSE 10



TEC -SW

TECHNICAL EDUCATION RESEARCH CENTER — SOUTHWEST
4201 LAKE SHORE DRIVE WACO, TEXAS



COURSE MODULES

COURSE 10 POWER PLANT SYSTEMS

- MODULE 10-1 Power Plant Fundamentals
- MODULE 10-2 Power Plant Thermal Cycles
- MODULE 10-3 Turbines and Generators
- MODULE 10-4 Heat Exchangers and Condensers
- MODULE 10-5 Pumps
- MODULE 10-6 Valves and Piping
- MODULE 10-7 Electrical Transmission and Distribution Systems
-  MODULE 10-8 Power Plant Fundamentals (Fossil-Fuel Energy Efficiency)
- MODULE 10-9 Fossil Plant: Auxiliary Discussions

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Technical Education Research Center
Southwest
4201 Lake Shore Drive, Suite 111
Waco, Texas 76710



INTRODUCTION

Electrical power generating plants the world over (except for hydroelectric plants and a handful of motor-driven generators) depend upon steam for energy transfer - from the potential energy of a fuel to the kinetic energy of a spinning turbine. And, with the growing exception of nuclear-fueled power plants, the fuels used are hydrocarbons - petroleum and coal based fuels, which are described more fully in Module 10-9 of this Course.

Except for this manner of fueling the boilers for steam generation, all steam electrical power generating plants operate on the same basic principle. This module presents that operating principle as a percent efficiency, or ratio of energy in (as fuel) to energy out (as distributable electricity).



MODULE PREREQUISITES

The student should have completed a course in basic algebra and Module 10-1, 10-2, 10-3 and 10-4 of this Course.



OBJECTIVES

Upon completion of this module, the student should be able to:

1. Compare energy efficiencies of at least two types of power plants.
2. List areas of energy losses and internal power consumption within a steam electric power plant.
3. Given the appropriate energy loss and internal power consumption data, calculate energy efficiency of a steam electric power plant.



$$e_k = \left(\frac{m}{2}\right)S^2$$

Equation 10-8-1
(Equation = Eq.)

where

e_k = kinetic energy.

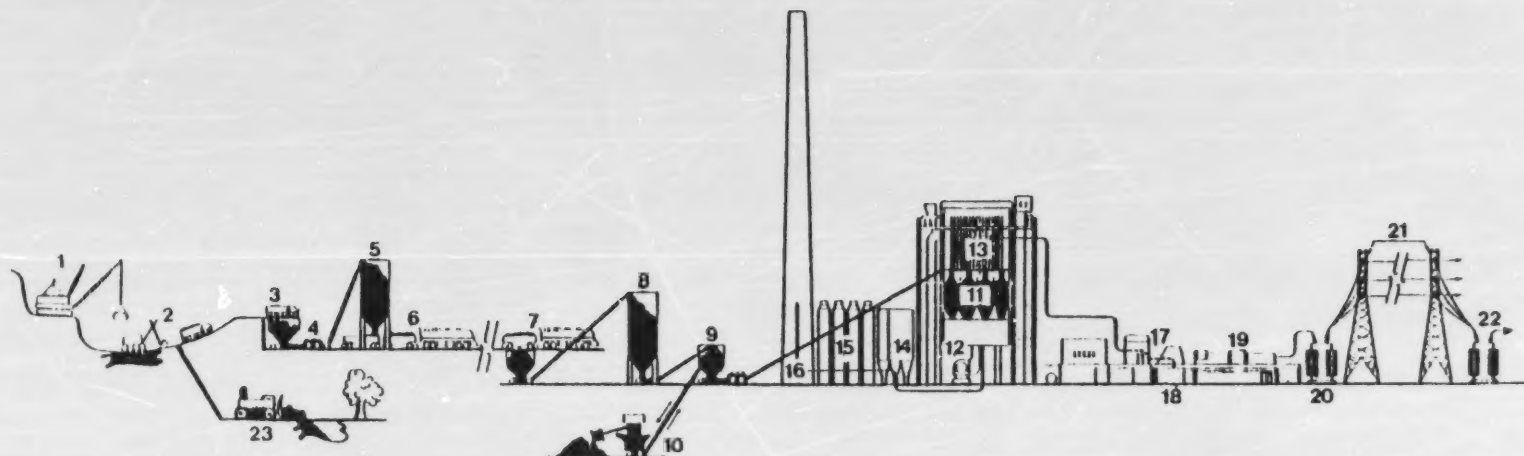
m = mass.

S = speed (at which mass is moving).

This equation conveys an efficiency limitation that affects steam turbine performance. There are other factors - from one end of the energy transformation cycle (hydrocarbon fuel to electricity) to the other - that severely limit power plant efficiency. Thus, the total thrust of facility and equipment design, construction and operation is to minimize these limiting factors.

ENERGY TRANSFORMATION CYCLE

For simplicity, the energy transformation cycle followed through (Figure 10-8-1) begins with coal - the most common power plant energy source. It could as well have been residual oil or natural gas, both of which are waning in popularity as stoker fuels, but still provide a significant portion of America's power plant potential energy supply.



1. DRAGLINE used for removing soil that covers the lignite.
2. SHOVEL for loading lignite into haulers.
3. TRUCK HOPPER. Haulers dump lignite into this hopper which feeds into the primary crusher.
4. PRIMARY CRUSHER crushes lignite to less than six inch pieces.
5. TRAIN LOADING SILO in fuel operations area is fed by conveyor from primary crusher.
6. RAILROAD CARS are loaded with 100 tons of lignite in about a minute and are pulled by electric locomotives.
7. TRAIN UNLOADING HOPPER is located at the plant.
8. SURGE SILO receives lignite from the train unloading hopper and serves as an intermediate storage point.
9. SECONDARY CRUSHER reduces lignite pieces to less than three-fourths of one inch. If lignite is not needed by the unit, it can be conveyed to a working stockpile before being crushed.
10. STACKER RECLAIMER is used to stockpile lignite in excess of plant needs and to recover from stockpile for plant use when required.
11. SILOS for lignite storage are on the boiler above pulverizers which grind the lignite to the consistency of face powder before it goes to furnaces.
12. FANS for blowing lignite into furnace to burn and to supply air for combustion.
13. BOILER makes high pressure steam from the heat produced from burning lignite.
14. ELECTROSTATIC PRECIPITATORS are used to remove fly ash coming from boiler furnace.
15. SCRUBBERS are used to remove sulfur dioxide from combustion gases before they are dispersed by the stack.
16. STACK is 450 feet tall with inside diameter of 23 feet at the top.
17. TURBINES are run by steam from boiler at 3,500 pounds per square inch pressure at 1,000 degrees. The turbine drives the generator.
18. CONDENSERS are used to convert steam back to water for reuse in the boilers. Water from the lake goes through these condensers and back to the lake after condensing the steam.
19. GENERATORS are kept at a constant speed of 3,600 revolutions per minute by means of a governor on the turbine. The power is generated at 20,000 volts.
20. POWER TRANSFORMERS used to raise generator voltage of 20,000 volts up to 345,000 volts.
21. TRANSMISSION line to transmit power at 345,000 volts to distribution substations.
22. DISTRIBUTION SUBSTATIONS located in the various cities and towns to reduce the transmission line voltage to distribution voltage for use in homes, farms, businesses and industries.
23. ENVIRONMENTAL RECLAMATION returning mined-out land to an "as good as or better than" condition relative to its premining use.

Figure 10-8-1. How lignite is mined and used to generate electricity.

The low-grade coal (lignite) used in many new power plants undergoes numerous operations prior to its arrival in a power plant fuel reservoir. On-site, it is pulverized for more effective and more efficient burning. And it is the burning that begins the energy transformation process.

Rapid combustion of the fuel releases its stored (potential) energy in the form of heated gases - the desired products of combustion are hot gases. These gases, flowing around the heat-exchanging membranes of a boiler convert water into steam. Through normal expansions, the steam flows rapidly through a system of tubes and nozzles, forcefully impinging against turbine (fan) blades, causing them to move.

Movement of the turbine blades causes the turbine shaft to rotate. This shaft is connected directly to the generator shaft. Thus, the generator is rotated, generating electrical output. This generation output, in America, is normally 1380 volts.

About ten percent of this generated power output is consumed in power plant operation. The balance is distributed as described in Module 10-7. Overall energy efficiency estimates (energy out as a percentage of energy in) for modern coal-fueled plants are generally stated in the 25 to 35 percent range. This efficiency may be calculated as follows:

$$\frac{E_{in} - E_{out}}{E_{in}} = \% \text{ Efficiency} \quad \text{Eq. 10-8-2}$$

ENERGY LOSS POINTS

As stated previously, energy losses occur throughout the transformation cycle. But the fundamental law of energy conservation insists that energy is neither destroyed nor created. The sum of all energy (potential, kinetic, thermal, chemical and electrical) entering a power plant must be exactly the same as the sum of all energy leaving (or lost in) a plant. Thus, if one pound of coal, containing 13,500 Btu, is stoked into the furnace, the electrical equivalent of 13,500 Btu should be distributed from the plant. But, in fact, only about the equivalent of 4,000 Btu exit the plant as distributable electricity. The other Btu's are "lost" within the plant in a variety of ways.

FURNACE LOSSES

Hydrocarbon fuels burn with various efficiencies. Bituminous coal (13,500 Btu/lb), when pulverized and properly supported by oxygen, burns with an 85 to 90 percent efficiency - the balance is ash and pollutants, which must be properly disposed. The 85 to 90 percent useful products of combustion undergo losses through radiation, absorption and dissipation (as flue gases).

Overall furnace losses, for this fuel, may be as much as 30 percent. For other hydrocarbon fuels, the efficiency losses may be more (45 percent for lignite) or less (15 percent for some natural gases).

STEAM-CYCLE LOSSES

The steam cycle, which includes the boiler and all its associated piping, condensers, and various heat exchangers, and the cooling-water system, suffers thermal losses through radiation and absorption, and is especially susceptible to friction losses - fluid flow through miles of conduits is retarded by both turbulence and drag. Energy losses in this cycle are extremely difficult to calculate, but are generally considered to be in the 25 percent range.

TURBINE ROTATION LOSSES

Major losses associated with this system, once it has obtained operational rotation speed, have to do with acceleration and deceleration and with auxiliary equipment operation. By using the equation provided at the beginning of this module, general turbine efficiency may be determined to be about 80 percent.

GENERATOR LOSSES

Electrical "drag" losses in any generator or motor are significant. When coupled with mechanical drag (friction) losses, the result is often an efficiency ratio in the 60 percent range.

CUMULATIVE LOSSES

As noted, about 10 percent of all electricity generated in a power plant is consumed by the plant. Another 5 to 10 percent may be written off as thermal losses in the main

transformer, bus bars and other controlling and switching equipment within the plant or in the adjacent switchyard.

By a series of calculations, the cumulative thermal losses and internal consumption are shown to account for approximately 70 percent of the energy input into the power plant. Conversely, energy efficiency may be shown to be approximately 30 percent. This efficiency represents a considerable increase over the 5+ percent obtained only a few decades ago, indicating that the thrust for greater efficiency has been productive. (The most modern nuclear-fueled power plants enjoy energy efficiencies only in the 30 to 35 percent range.)



EXERCISES

None.



MATERIALS

None.



ENERGY EFFICIENCY CALCULATION

Given:

Furnace loss (L_F)	= 25%
Steam-cycle loss (L_S)	= 25%
Turbine rotation loss (L_T)	= 20%
Generator loss (L_G)	= 40%

Find:

Energy efficiency of power plant (energy out, E_{out} , and a percentage of E_{in}).

Solution:

$$\begin{aligned} \text{Energy in } (E_{in}) &= 100\% \\ E_{in} - L_F &= 100\% - 25\% \\ &= 75\% \\ (E_{in} - L_F) - L_S &= 75\% - (0.25 \times 75)\% \\ &= 75\% - 18.75\% \\ &= 56.25\% \\ [(E_{in} - L_F) - L_S] - L_T &= 56.25\% - (0.20 \times 56.25)\% \\ &= 56.25\% - 11.25\% \\ &= 45\% \\ \{[(E_{in} - L_F) - L_S] - L_T\} - L_G &= 45\% - (0.40 \times 45)\% \\ &= 45\% - 17\% \\ E_{out} &= 28\% \end{aligned}$$

If L_F , L_S , L_T and L_G are each improved by one percent, what is cumulative energy efficiency?



DATA TABLE

None.



REFERENCE MATERIALS

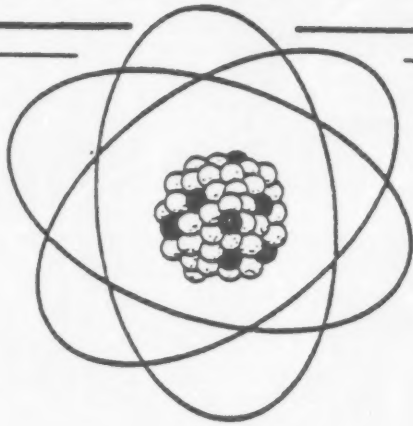
None.



1. In general, are coal-fueled power plants more energy efficient or less energy efficient than the following:
Natural-gas-fueled power plant? _____
Nuclear-fueled power plant? _____

2. List four major systems in a power plant where energy loss occurs:

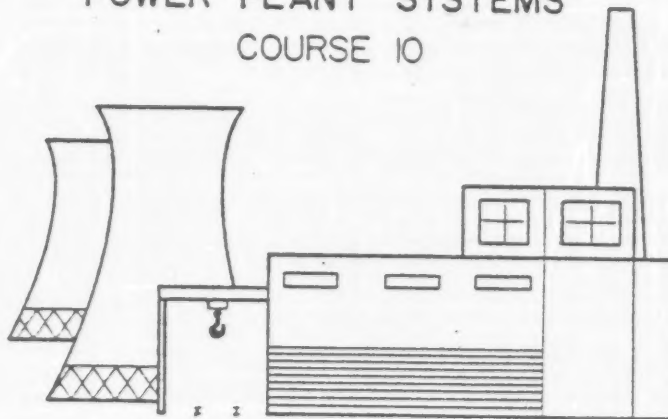
3. Approximately what percent of the generator's total electrical output is consumed by plant operation?



NUCLEAR TECHNOLOGY

MODULE 10-9 FOSSIL PLANT: AUXILIARY DISCUSSIONS

POWER PLANT SYSTEMS
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Waco, Texas 76710



A boiler, in a fossil-fueled power plant, is that part in which water is converted into steam. Boilers usually consist of metal shells, drums, headers and tubes that form containers for steam and water under pressure.

In a pressurized steam boiler system, the water is converted to steam by heat from a burning fissioning fuel. The steam is used to convert thermal energy to mechanical energy, and then to electrical energy. Fluids other than water can be used in boilers, but water is used most frequently because of its economy, and its suitable thermodynamic characteristics.

Sizes of boilers vary from small portable units to installations 200 feet high. Such a large unit would be delivered in pieces and sections to a construction site for assembly and installation.

Because boilers operate at high pressures, its parts must be made strong enough to withstand great stresses and extreme temperatures. Overheating or oxidation of boiler material must be avoided to prevent loss of strength.

Safety of design, construction, operation, or maintenance of a boiler comes under the scrutiny of appropriate governmental agencies, industrial associations and insurance underwriters. The American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code is the American standard for boiler construction, installation and operation.



MODULE PREREQUISITES

None.



OBJECTIVES

Upon completion of this module, the student should be able to:

1. List major boiler design types.
2. Define:
 - Economizer.
 - Superheater.
 - Reheater.
 - Blowdown.
 - Vapor separators.
 - Supercritical.
 - Petroleum and gaseous fuels.
3. List major classifications of fossil fuels, including various types of each.
4. State how heating value of coal is determined, and why.
5. List and describe combustion reactions that take place in a boiler.
6. After visiting a local fossil-fueled power plant, write a brief report, stating type of boiler used, type of fuel used (and why).



BOILER DESIGN

There is no one ideal boiler design for general application; consequently, several designs are available to the commercial market. Service requirements of a particular installation provide the determining factor in boiler design selection. Various boiler types are examined in the following discussions.

WATER-TUBE BOILER

In a water-tube boiler, water circulates through tubes, and heat is applied to the outsides of the tubes (Figure 10-9-1).

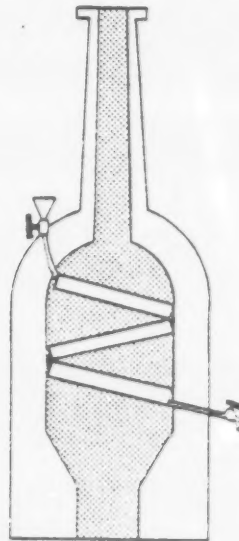


Figure 10-9-1.
Water-tube boiler.

A prominent feature of this boiler is the use of small tubes (outside diameter of three inches or less). These

tubes, exposed to the boiler's combustion process, are connected to steam and water drums, shielded from the combustion gases. The shielding restricts possible boiler failure to the small tubes. In the event a failure does occur, released energy is small and hazards are minimized.

The water-tube design is subject to lower stresses from pressure and from temperature differences because of the small diameter of the tubes, which allows an arrangement that accommodates changes in pressure and temperature.

Water-tube boilers are more suitable for large-capacity, high-pressure applications requiring a high margin of safety.

STRAIGHT-TUBE BOILER

A straight-tube boiler (often referred to as a header-type boiler) facilitates inspection and cleaning through handholes located in tube ends of headers. A header is like a metal drum with a small interior diameter, usually under 24 inches. Headers are used in modern steam boilers for joining two or more boiler circuits.

In many straight-tube boiler designs, the tube bank is baffled. This modification improves heat transfer and increases efficiency (Figure 10-9-2).

Straight-tube boilers are not suitable to high-pressure operation; capacity is limited by space requirements.

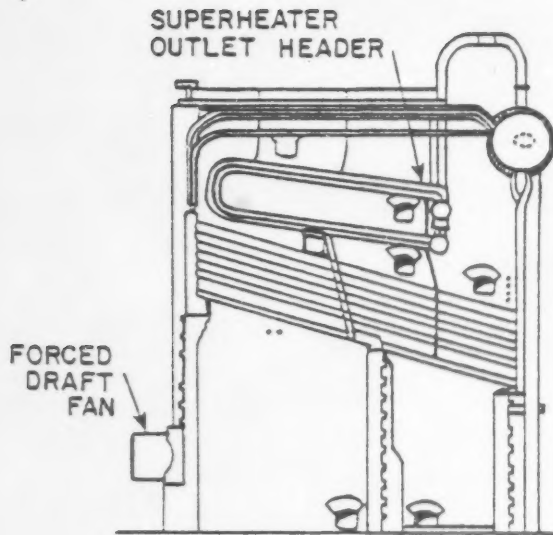


Figure 10-9-2.
Straight-tube boiler.

BENT-TUBE BOILER

This boiler design (Figure 10-9-3) incorporates drum-and-tube construction. The drum can be as large as space permits. Steel plates are pressed into half cylinders, or shells. These shells, which can be up to 42 feet in length, are joined by welding two half shells together along the longitudinal axis. Desired length is obtained by joining as many shell ends as needed.

The larger slope of the tubes in a bent-tube boiler, or even the use of vertical tubes, decreases the possibility of steam pocket formation. Without steam pockets, tube exteriors can absorb heat at a greater rate. This type of boiler can be used with both high- and low-pressure steam; also, it can be used for capacities from a few thousand pounds of steam per hour up to a million or more pounds

of steam per hour.

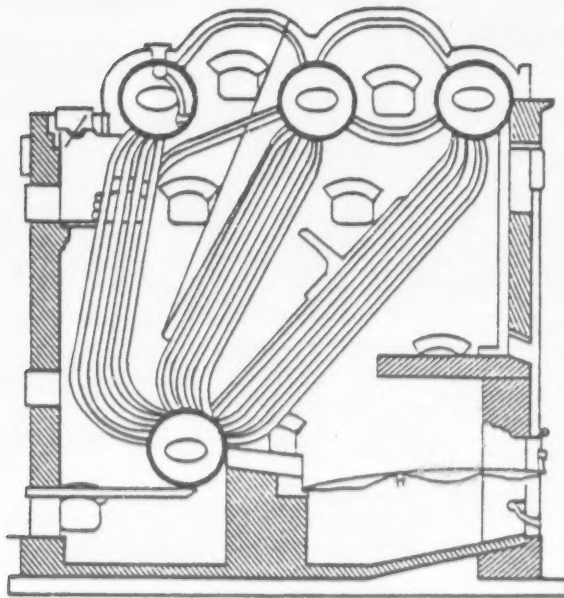


Figure 10-9-3.
Bent-tube boiler.

A bent-tube, drum-type boiler can be designed to meet almost any space allotment and can be planned to include such heat-absorbing components as economizers, superheaters and reheaters.

SHELL BOILER

A shell boiler is a closed vessel containing water, with part of the vessel exposed to heat. It is not suitable for significant power plant use.

FIRE-TUBE BOILER

The amount of surface exposed to heat on a shell-type boiler can be increased by passing hot gases from the fire through the inside of tubes positioned within the shell. Tubes can be placed in vertical, horizontal, or inclined positions; however, the most common arrangement is the horizontal-return-tubular boiler (Figure 10-9-4).

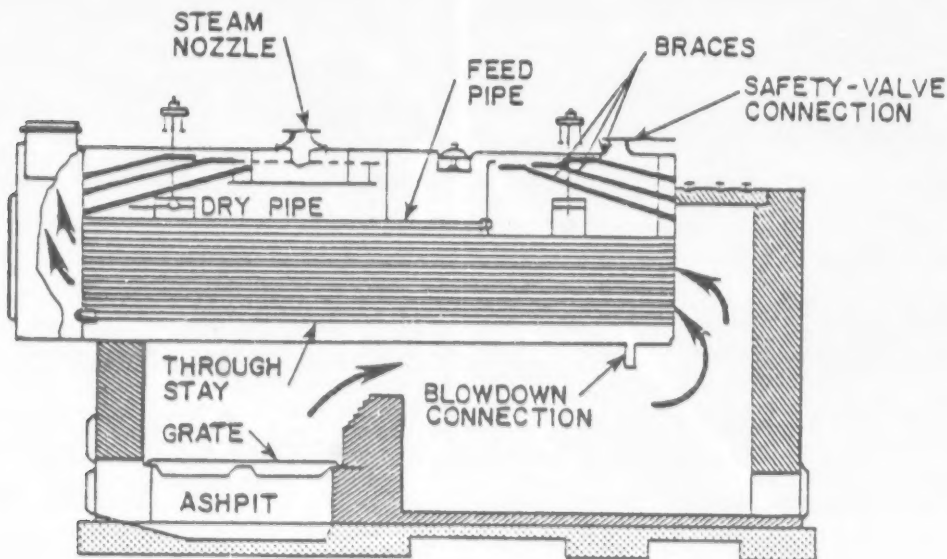


Figure 10-9-4. Model of horizontal-return-tube boiler.

Fire-tube boilers are used extensively to supply steam for space heating and are still in use in some railroad locomotives for steam outputs.

BOILER COMPONENTS

A number of engineering innovations designed to absorb heat and increase efficiency of boilers have been developed.

An economizer, in a steam-generating unit, is a separate bank of tubes designed to absorb heat from the products of combustion and add that heat to the feedwater before the water enters the boiler. In effect, the economizer is a feedwater heater. It receives water from the feedwater pump and delivers the water at a higher temperature to the steam generator or boiler (Figure 10-9-5). The economizer

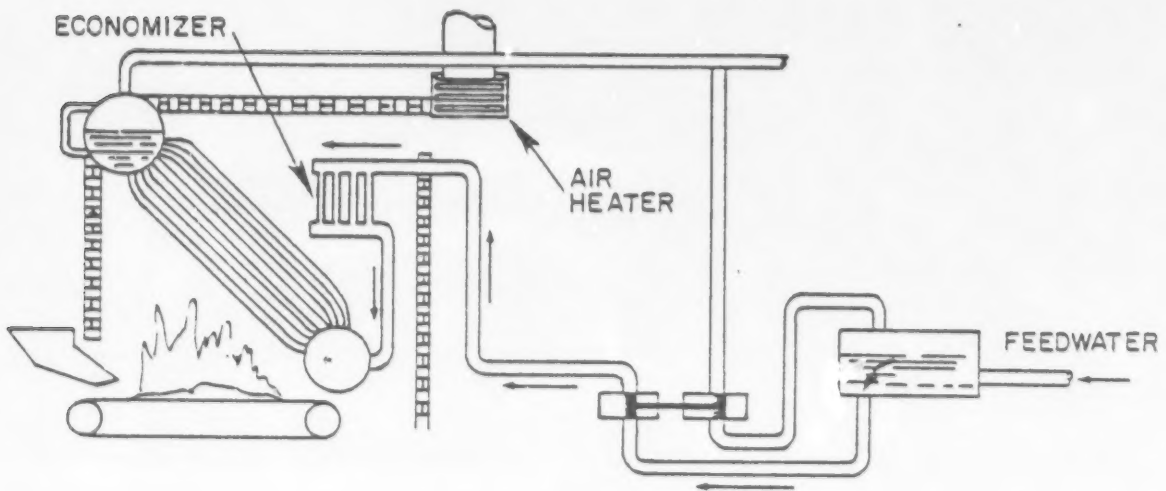


Figure 10-9-5. Representative position of economizer.

is positioned in the path of combustion gases traveling toward the air heater and the stack (chimney). Most of the heat in these gases is absorbed by boiler tubes, but

not all. By directing travel of the gases around the economizer, some of the remaining heat is absorbed by it, with a resultant increase in boiler efficiency.

A superheater is used to raise steam to a higher temperature than that at which it was produced in the boiler. A superheater may consist of one or more stages of tube banks arranged to effectively transfer heat from the products of combustion. All modern fossil-fueled plants use superheated steam. The final stage of a superheater is generally positioned in a zone close to the furnace enclosure, or it projects into the furnace with "loops."

Most modern power plants utilize a second superheater, called a reheater, to further heat steam after it passes through a portion of the turbine. In large turbines, formation of drops of water near the exhaust end of the turbine can cause damage. Through addition of more heat, the steam is "dried."

COMBUSTION REACTIONS IN A BOILER

To generate power, useful heat is produced by combustion. Combustion may be defined as rapid chemical combination of oxygen with the combustible elements of a fuel. Most common fuels (coal, gas, wood, and their various derivatives) contain the three chemical elements of carbon, hydrogen and sulfur, which unite with the oxygen of air to produce heat. (In most fuels the main chemical elements are carbon and hydrogen; sulfur content is low enough to be considered insignificant.)

Complete combustion is achieved when the combustible elements and compounds combine with an adequate supply of

oxygen. Sufficient time, space, mixing and a temperature high enough to ignite the components must be provided.

Factors governing combustion in a boiler include:

- Fuel properties.

- Air quantity.

- Blowers.

- Fuel, air and furnace pressures.

- Fuel, furnace and gas temperatures.

- Furnace dimensions.

- Number, type and size of burners.

- Flame characteristics.

- Heat release and control.

- Furnace efficiency.

Air and fuel are burned in the combustion chamber. Products of this combustion (in the form of hot gases) leave the chamber and pass over heating tube surfaces in the gas circuit. These hot gases, flowing through the boiler, are cooled from a maximum combustion chamber temperature to a minimum stack temperature. Heat lost by the gases is absorbed by water in the boiler. Incoming feedwater is heated to temperature of water in the boiler, which is the temperature of steam. Any liquid water at the heated surfaces absorbs heat to form vapor, or steam bubbles. The vapor, or bubbles, rise to water surface for release into the steam space. This circulation is a result of the vaporization process and is called natural circulation. A water-steam flow pattern that depends on mechanical means, such as pumps, is called forced circulation.

BLOWDOWN VAPOR SEPARATORS

Because water is continually cycled through a boiler, impurities may concentrate in the boiler water. To minimize collection of contaminants, it may be necessary to blowdown the boiler. Any necessary blowdown includes the steam drum. The steam drum is the vessel in which saturated steam is separated from steam-water mixture and into which feedwater is introduced. Blowdown of the boiler can be done periodically or continuously.

Small power plants use a periodic system in which a blow-off valve is opened for a few seconds to blow out the water in the lowest part of the boiler where the collection of impurities is concentrated.

In large plants, a continuous blowdown system minimizes the amount of heat lost during blowdown. This reduction is accomplished by continuously withdrawing a small amount of water from the boiler bottom.

Before the withdrawn water is run into a sewer, it is run through a heat exchanger to draw heat for transfer to incoming feedwater.

SUPERCRITICAL

The process of boiling water to make steam is usually done at pressures below critical, which is 3206.2 psia (absolute pressure). But progressive change has introduced supercritical operation.

When pressures approach or exceed supercritical, differences between the densities of water and steam become so small that a pump is required to ensure positive circulation; therefore, a mechanical means of moving water with-

in the circuits is employed.

Supercritical steam generators have no steam or separating drums and require the highest purity of feed and boiler water. The purity is necessary to avoid deposits in heated circuits or to restrict transport of solids to the turbine.

FUELS

All power plant energy originates as a fuel. The following discussion relates to the fossil fuels only.

PETROLEUM

Petroleum consists almost exclusively of the chemical elements hydrogen and carbon, commonly called hydrocarbons. The hydrocarbons are a diverse family of materials, such as natural gas, gasoline, benzol, kerosene, lubricating oils, paraffin wax, naphthalene, turpentine and rubber.

Most scientists accept the organic theory of petroleum formation. According to this theory, petroleum was formed over a span of millions of years in prehistoric waters that covered most of the earth. Tiny plants and animals lived in the shallow depth of the water and along the coastlines. As the plants and animals died, their remains settled on the muddy bottoms of the water. Sediment, in the form of fine sand and silt, drifted down over the plant and animal matter. As the amount of sediment grew into heaps and piles, the amassed weight pressed them into hard, compact beds of sedimentary rock. Throughout the rock-forming process, bacteria,

pressure, heat and other natural forces worked to change the plant and animal remains into petroleum.

The modern petroleum industry refines this crude oil taken from the earth to produce useful products to meet requirements of the commercial market. Hydrocarbons give special characteristics to the parts, or fractions, of petroleum. Some of these fractions, such as gasoline and kerosene, need little change, but refineries must change other fractions before they can be used. Separating the fractions and converting them to useful products are the main functions of an oil refinery. Gasoline and diesel oil are refinery products, both are important sources of heat energy, but neither is used normally for steam generation.

Fuel oils are the petroleum products used to generate electrical power. The oils are produced to comply with the several specifications prepared by the American Society of Testing Materials and adopted as a commercial standard by the United States Bureau of Standards. The standards have been revised several times in past years, and further alterations are expected to satisfy international changes in supply and demand.

The two primary classes of fuel oils are distillate and residual. Distillate fuel oils are made up entirely of material that has been vaporized in a refinery distillation tower. These fuels are clean, free of sediment, comparatively low in viscosity, and free of inorganic ash. Residual fuel oils contain fractions that cannot be vaporized by heating. These fractions are black and heavy and retain any inorganic ash components that were in the original crude oil.

Fuel oils are graded according to gravity and viscos-

ty, the lightest being No. 1 and the heaviest being No. 6. The latter is most widely used for steam generation because it is least expensive of the graded oils.

Fuel oils are burned efficiently by atomizing them into fine droplets and injecting the droplet spray into a combustion chamber with a stream of combustion air. The oils are blended to meet certain tests and specifications to ensure an efficient burning, and also to ensure that they can be handled safely and easily and that they will meet air-pollution regulations.

The heavier grades of fuel oil have high viscosity and must be heated just to be pumped and atomized.

GASEOUS FUEL

Natural gas is often found on top of oil deposits, or dissolved in them, because the same natural forces formed both fuels. But, paradoxically, there are many natural gas wells that yield no petroleum.

Pure natural gas, like solid petroleum, is made up of the chemical elements hydrogen and carbon. Natural gas is composed chiefly of methane - the lightest hydrocarbon. Other gaseous hydrocarbons usually present in natural gas include ethane, propane and butane. Common types of fuel gases include natural gas, LP (liquefied petroleum) gas, and refinery gas.

There is no single composition that might be termed typical natural gas, but the term has been adopted to apply to gases commonly associated with geological formations containing petroleum. Natural gas is considered ideal for heating because of its cleanliness, ease of transportation,

high heat content, and high flame temperature.

LP gas is the term applied to certain specific hydrocarbons such as propane, butane and pentane. These fuels are gaseous under normal atmospheric conditions but can be liquefied under certain pressure at average temperatures.

Refinery gas is the description given to a group of gases obtained as byproducts during thermal processing of oil in a refinery. Primarily, they are used for heating refinery equipment. Refinery gas was formerly very important as a fuel gas but has been almost totally replaced by natural gas.

Other gaseous fuels in frequent use are coke-oven gas and blast furnace gas, both of which are used in steel production.

COAL

Coal is believed to have been formed in much the same way as oil. In early geological times much vegetation covered the surface of the earth. Successive layers of fallen vegetation piled one on the other to be mixed with sand and dirt. In the passing of years, these layers of vegetation were acted upon by effects of sun, wind and water, whose heat and pressure changed the vegetation to peat and then into coal.

Present standards call for two classifications for coal. The first is according to rank, which is determined by the amount of alteration and compaction the coal has undergone. North American coal may be ranked as follows:

Anthracite.

Bituminous.

Subbituminous.

Lignite.

Difference in rank is measured by a progressive increase in water and in volatile matter, and by a progressive decrease in carbon and heat content. Relative amounts of water, volatile matter, carbon and heat content determine how well the coal will withstand transportation handling and storage, and how well it will burn.

Anthracite is classified as a hard coal and makes up only a small part of the world's coal supply. It is very high in carbon and is low in water and volatile matter. Anthracite is jet black in color and is free of soot when burning. It requires more heat and effort to begin combustion, but, when started, it burns with a steady, clean, hot blue-colored flame, and it burns longer than coal of lower rank. Anthracite is more expensive than bituminous coal.

Bituminous coal, classed as a soft coal, is the most plentiful rank of coal. It is the chief fuel in industrial plants that generate electricity with steam. Bituminous coal withstands transportation well, and has a slightly higher heat content than anthracite.

Subbituminous coal has a lower heat content than bituminous. It possesses a tendency to crumble when exposed to weather and also tends to crumble during transportation. Subbituminous is not mined extensively where coal of a higher rank is available.

Lignite is a brown colored coal with a distinctive woody texture. It is little changed from peat. Lignite has a high moisture content; it also crumbles when exposed to weather and during transportation, and is subject to spontaneous combustion.

The second method of coal classification is according to grade. Grade is determined by evaluation of ash-producing substances, sulfur and other detrimental ingredients.

Grade is a term used to express quality. (Rank is used to express degree of coal alteration and compaction.) It is possible that a low rank coal such as lignite may be of high grade, and a high rank coal such as anthracite may be of low grade.

Relative amounts of sulfur- and ash-producing substances in a coal are the primary factors in determining a coal's grade. High-grade coal has less sulfur and produces less ash than low-grade coal; therefore, the high grade is more desirable and more expensive.

Sulfur is an undesirable ingredient of coal, even in small quantities. When coal is burned, most of the sulfur is discharged into the atmosphere as sulfur dioxide and sulfur trioxide - serious pollutants. When sulfur is combined with oxygen and water, it becomes sulfuric acid. This acid can corrode boilers in steam-electric power plants where coal is used as the fuel to heat boiler water.

Coal with a high content of ash-producing substances is undesirable because ashes add useless weight that must be handled both before and after burning. Some ash contributes to air pollution, and ash components may fuse to form clinkers that could foul grates and hinder the burning process.

Coal supplies the fuel used to generate over half the electric power in the United States. One ounce of coal makes as much electricity as 100 short tons of water falling one foot. The electric utility industry, as of 1973, used over 300 million tons of bituminous coal a year. Coal is necessary even for the production of atomic energy.

Millions of tons of coal are used each year to produce the electricity needed to operate U.S. uranium enrichment plants.



EXERCISES

Visit a coal- or lignite-fueled power plant; answer the following questions:

1. What type(s), rank(s) and grade(s) of fuel are used?
2. Where is the fuel mined?
3. How is it transported from mine to plant?
4. How is it "treated" or conditioned at the plant before being stoked?
5. What is fuel consumption rate (tons/day)?
6. How large is plant-site fuel reserve? How long will reserve last?
7. What is approximate sulfur content (ppm)?
8. What becomes of the combustion residue?
9. What type of boiler is used?



MATERIALS

None.



PROCEDURES

1. Use information and illustrations from this module to sketch the boiler system used in the plant visited (see Exercises); include all boiler components.
2. Under controlled laboratory conditions specified by instructor, burn fuel samples, including:
 - Anthracite coal.
 - Bituminous coal.
 - Lignite.
 - Residual oil.

Note 1) difficulty of ignition, 2) heat output and 3) pollutants and residue.



DATA TABLE

None.



REFERENCE MATERIALS

Babcock and Wilcox Company. Steam, Its Generation and Use.
New York: Babcock and Wilcox, 1974.

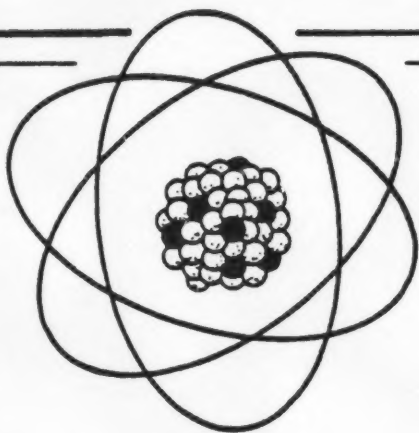
Blowdown.

Vapor separator.

Supercritical.

Hydrocarbon.

4. List the two major classifications of fossil fuels (give two or more examples of each):

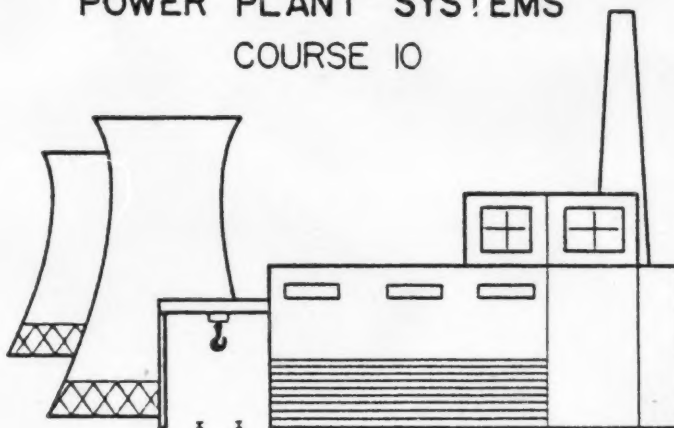


NUCLEAR TECHNOLOGY

INDEX

COURSE 10 - POWER PLANT SYSTEMS

POWER PLANT SYSTEMS COURSE 10



TEC-SW

TECHNICAL EDUCATION RESEARCH CENTER — SOUTHWEST

4201 LAKE SHORE DRIVE WACO, TEXAS

NUCLEAR TECHNOLOGY SERIES
INDEX
for
COURSE 10, POWER PLANT SYSTEMS (NINE MODULES)

NOTE: Each module in this Course is numbered separately, and the page numbers begin with page 1 in each module. Therefore, this Index lists for each entry the module number (underlined), followed by a comma and the page number. Figures and tables are listed by their numbers, followed by the module and page number in parentheses. A Master Index is available in a separate volume. This general index merges all index entries from the 35 Nuclear Courses. It is a valuable research tool, with which the student or researcher can locate all the references to any subject within the 35 Courses.

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